Orion MPCV Service Module Avionics Ring Pallet Testing, Correlation, and Analysis

The NASA Orion Multi-Purpose Crew Vehicle (MPCV) is being designed to replace the Space Shuttle as the main manned spacecraft for the agency. Based on the predicted environments in the Service Module avionics ring, an isolation system was deemed necessary to protect the avionics packages carried by the spacecraft. Impact, sinusoidal, and random vibration testing were conducted on a prototype Orion Service Module avionics pallet in March 2010 at the NASA Glenn Research Center Structural Dynamics Laboratory (SDL). The pallet design utilized wire rope isolators to reduce the vibration levels seen by the avionics packages. The current pallet design utilizes the same wire rope isolators (M6-120-10) that were tested in March 2010. In an effort to save cost and schedule, the Finite Element Models of the prototype pallet tested in March 2010 were correlated. Frequency Response Function (FRF) comparisons, mode shape and frequency were all part of the correlation process. The non-linear behavior and the modeling the wire rope isolators proved to be the most difficult part of the correlation process. The correlated models of the wire rope isolators were taken from the prototype design and integrated into the current design for future frequency response analysis and component environment specification.

Orion MPCV Service Module Avionics Ring Pallet Testing, Correlation and Analysis

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Agenda

- Background
- Correlation
- EFT-1 Configuration
- Conclusions
- Acknowledgements

Spacecraft and Launch Vehicle
Dynamic Environments Workshop

Background

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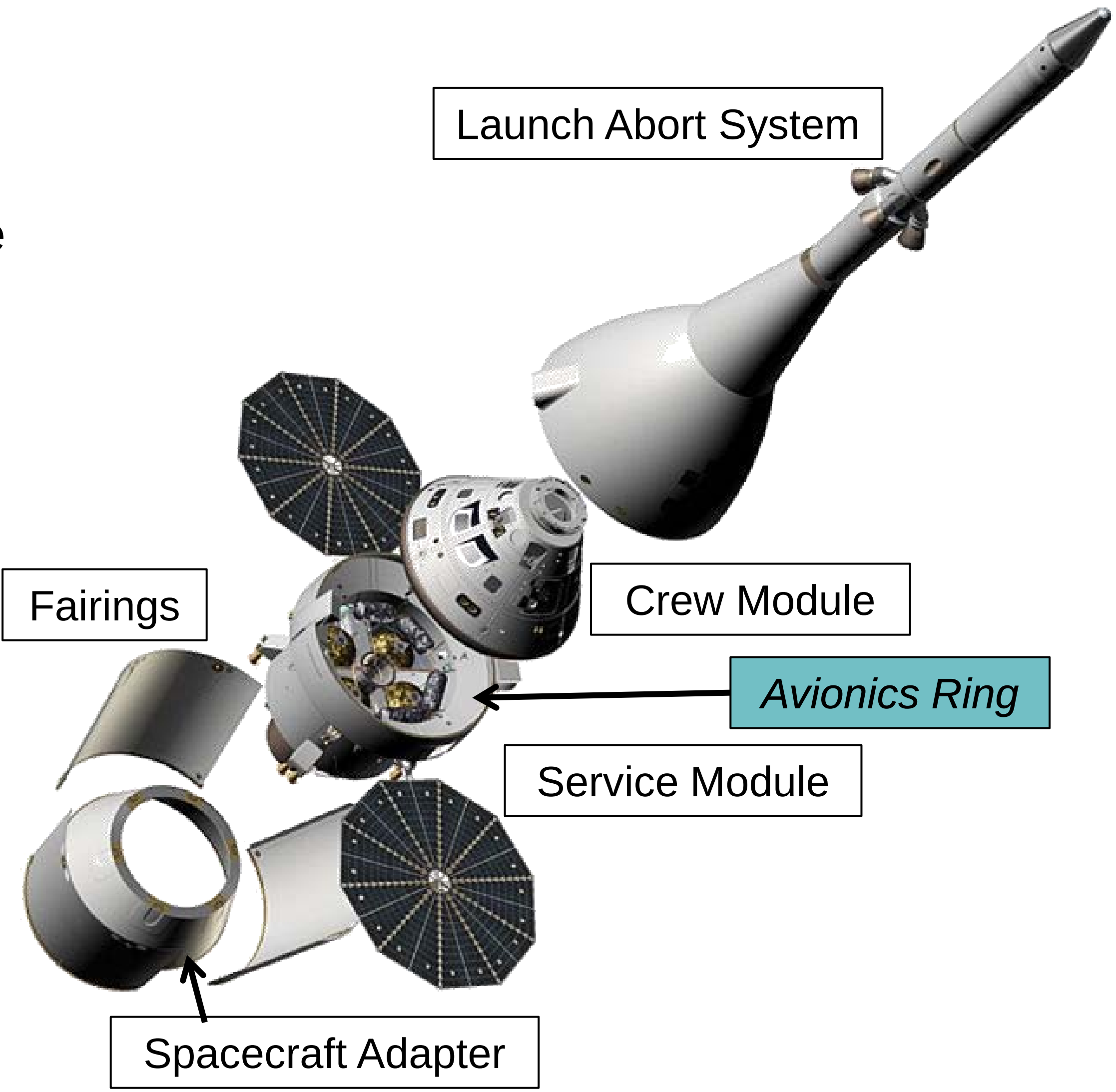
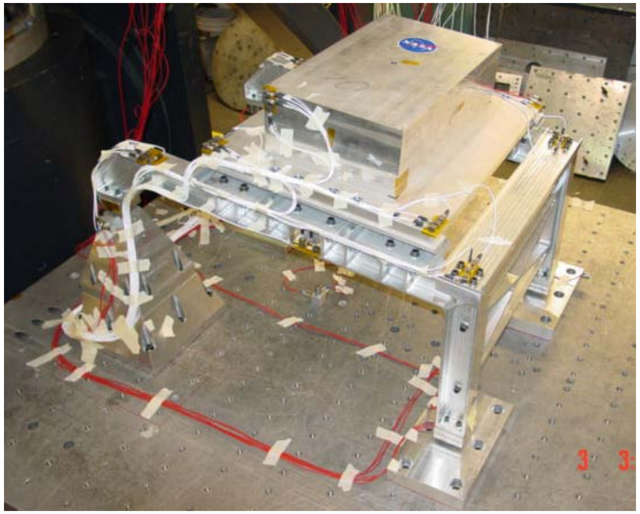
Orion Multi-Purpose Crew Vehicle (MPCV)

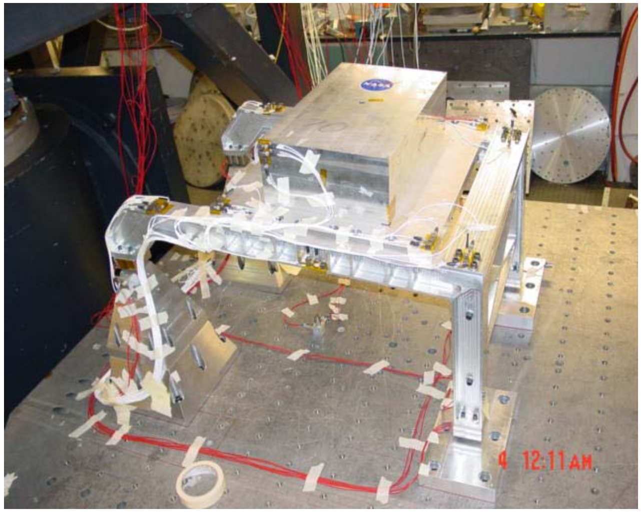
- Orion MPCV is currently being designed as NASA's next human rated spacecraft
- Service Module Avionics Ring houses many important power, life support, communications, and navigation packages
- Predicted environments resulted in needing an isolation system design to protect sensitive avionics equipment in the SM Avionics Ring
- Development testing performed on a avionics pallet design, utilizing commercial (off the shelf) wire rope isolators to prove feasibility and potential performance of wire rope isolators and pallet design



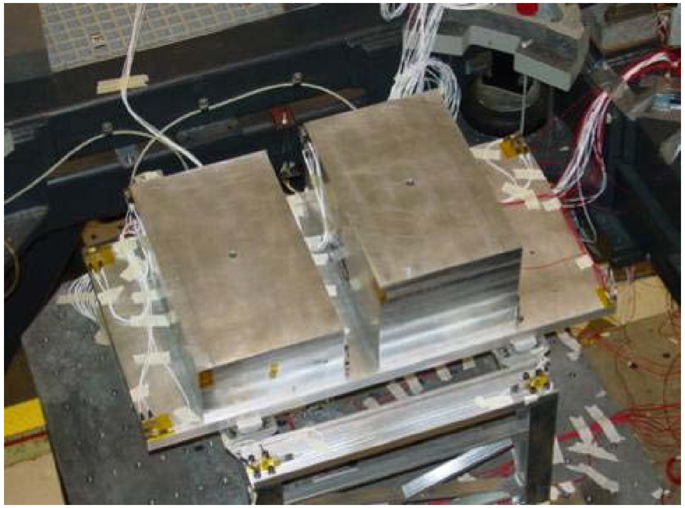
SM Avionics Pallet Test Configurations



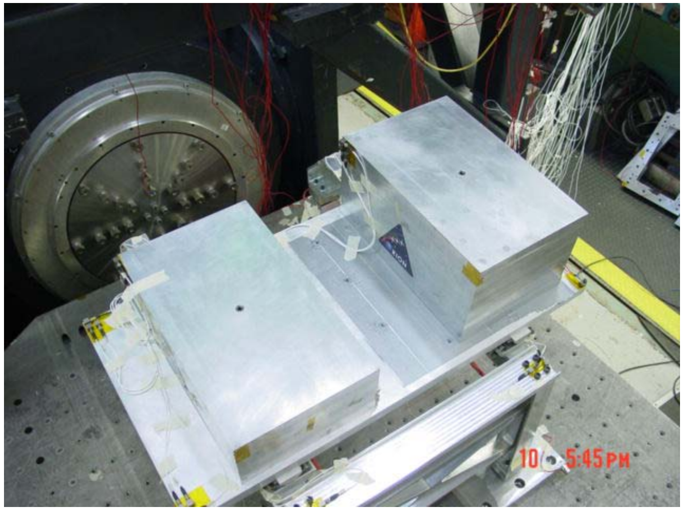
1) Small Pallet 70lb mass, isolated



2) Small Pallet 70lb mass, hard mounted



3) Large Pallet 70lb & 120lb mass, isolated



4) Large Pallet 70lb &120lb mass separated, isolated

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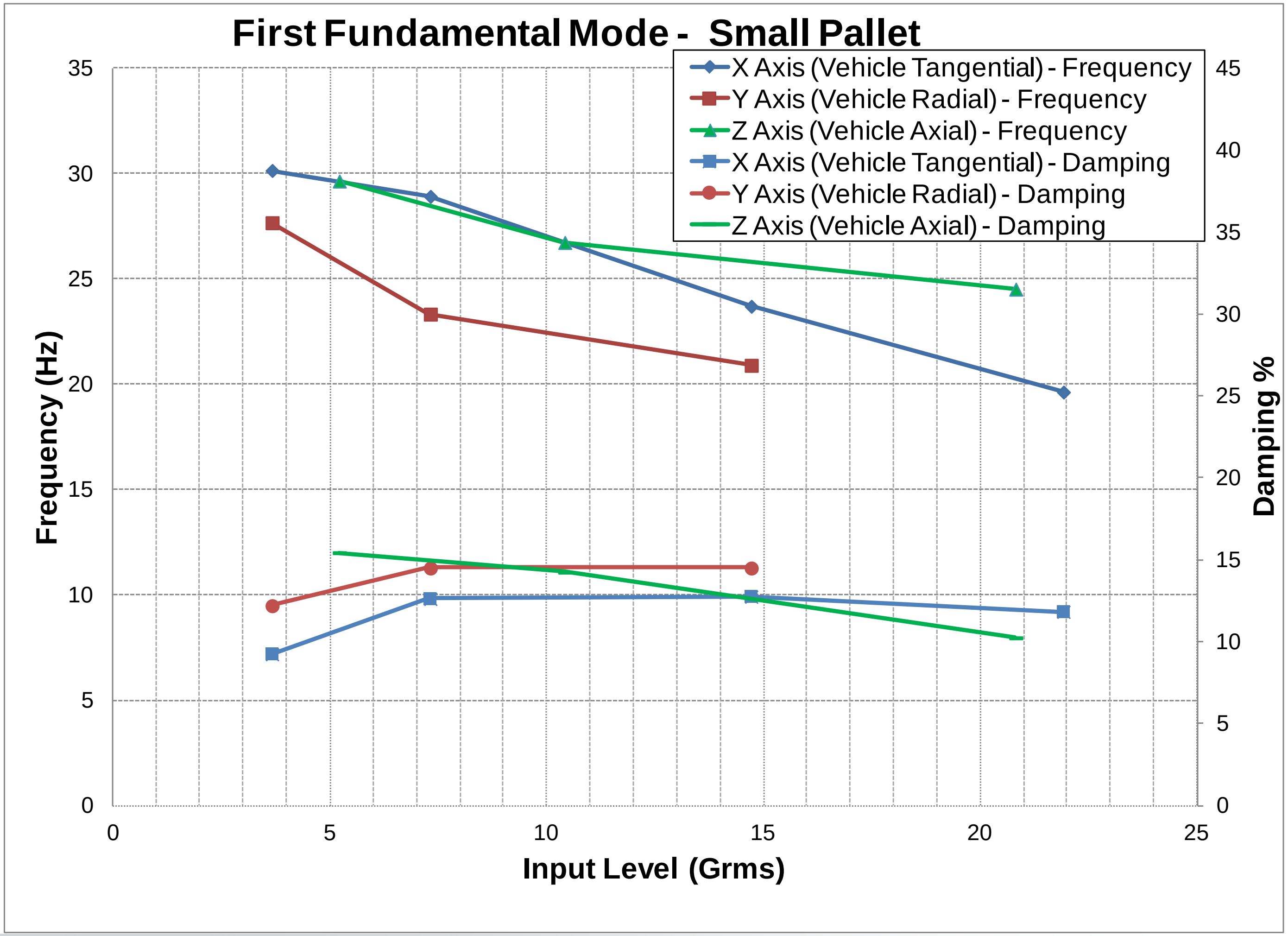
SM Avionics Pallet Test Results (1)

- Isolators displayed softening characteristics (i.e. modal frequencies of fundamental modes decreased as input levels increased).
- Isolator manufacturer provides a high damping value of $C/C_c \approx 0.20$ in literature for isolators → High modal damping also extracted from test data; expected to be lower



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SM Avionics Pallet Test Results (2)

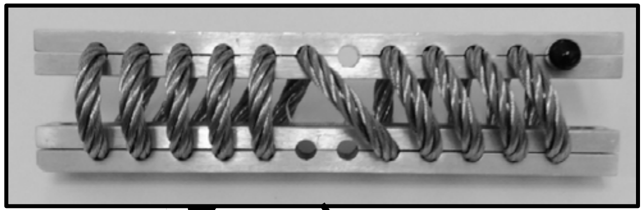
- Mass simulator had two accelerometers on opposite corners (front lower and rear upper corners)
- Accelerations were averaged to produce a representative C.G. mass response and used to create the results in the tables below → Hard Mounted vs. Isolated
- Large reductions in overall GRMS level seen at the avionics mass simulator

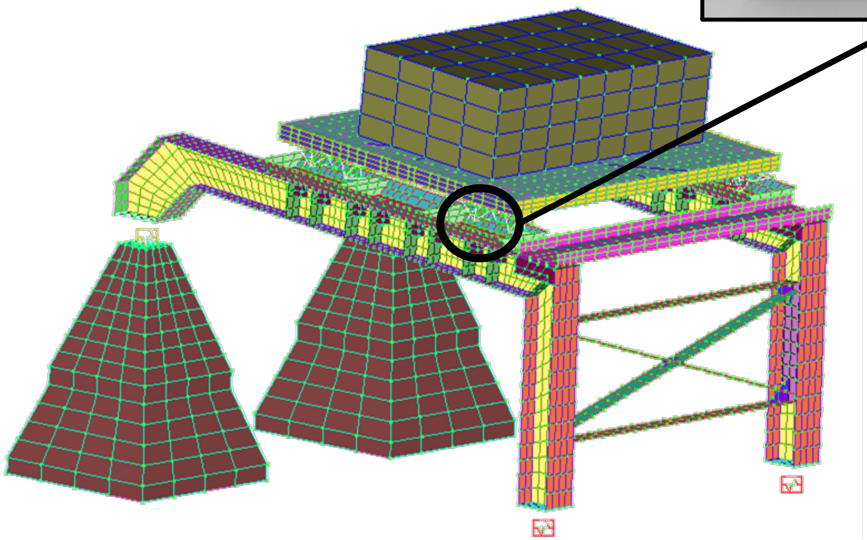
Run	Axis	Mount	C.G. Response (Grms)	Percent Reduction (Isolated/Hard	Reduction in dB (Isolated/Hard)
83 - 3.65Grms	X (Tangential	Isolated	0.52	**-72%**	**11**
105 - 3.65Grms	X (Tangential	Hard	1.86		
91 - 3.65Grms	Y (Radial)	Isolated	0.65	**-90%**	**20**
99 - 3.65Grms	Y (Radial)	Hard	6.79		
125 -5.2Grms	Z (Axial)	Isolated	2.20	**-88%**	**18**
117 - 5.2Grms	Z (Axial)	Hard	17.69		

Development test proved feasibility and demonstrated potential performance of the wire rope isolator and pallet design

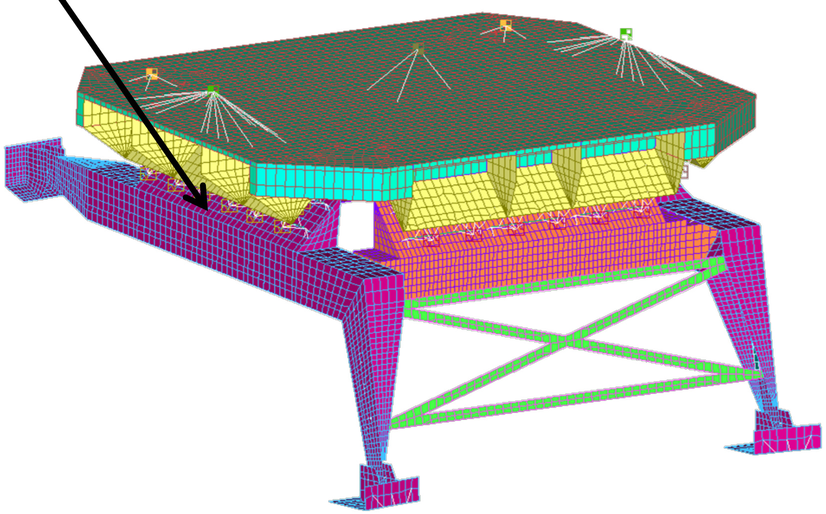
In-Line Task Objective

- Orion MPCV project requested isolator test data from March 2010 development test be correlated and used to create new component environments → Exploration Flight Test - 1 (EFT-1) Pallet Configuration uses M6-120-10 wire rope isolators
- <u>**Objective:**</u> Correlate FEM's to the NASA GRC SM Pallet test data, which include models of the M6-120-10 wire rope isolators. Extract the correlated M6-120-10 models from these correlated FEM's and integrate them into the EFT-1 SM Pallet model for frequency response analysis and generating component environments.





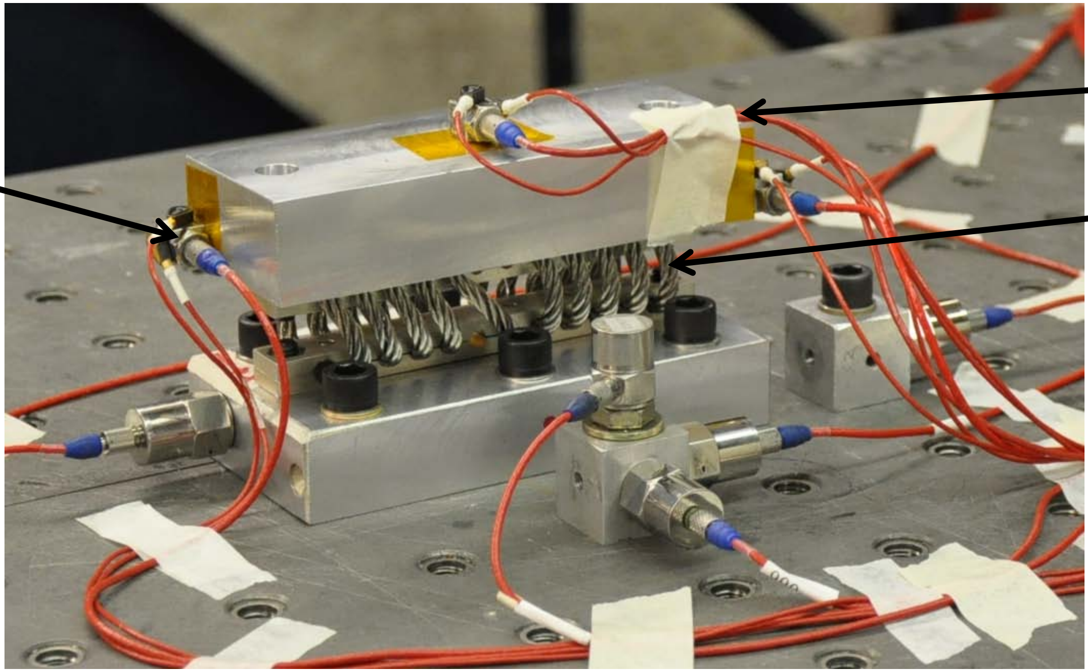
Small Pallet Configuration (March 2010)



EFT-1 Pallet Configuration

Single M6 Isolator Test Configuration

- Original objective of March 2010 SM Avionics Pallet test was to determine feasibility and potential performance of design → not to model/correlate isolators in great detail
  - *Testing met initial intent*
  - *Correlation work requested well after test completed and torn down*
- Single M6-120-10 isolator test performed to better understand isolators
  - *Due to schedule and cost constraints isolators were not able to be tested in a configuration to load isolators to the extent they were/will be loaded in the SM Avionics Ring*
  - *Ideally isolator would be dynamically tested/loaded to flight like levels with forces and displacements explicitly measured*



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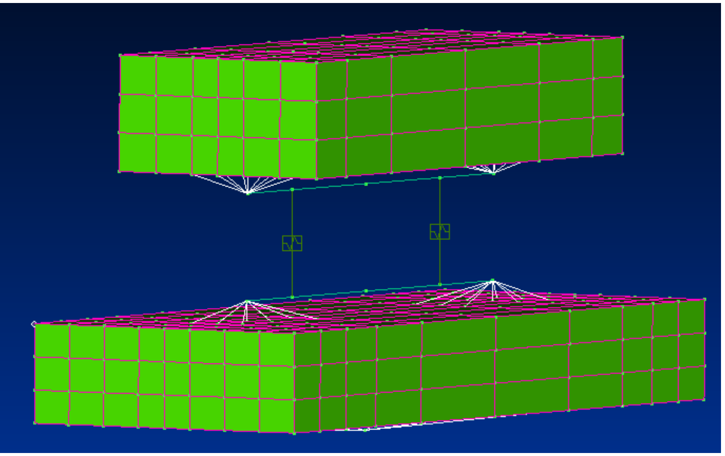
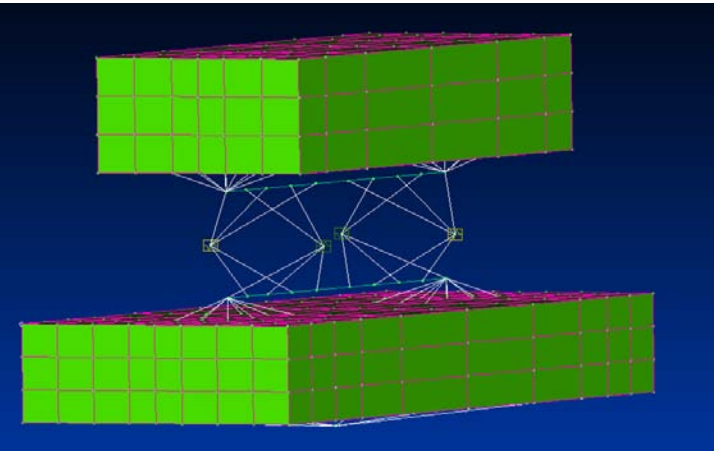
Single M6 Isolator Test Results



Two CBUSH Isolator FEM

MAC Matrix for Single M6 Isolator 2pt5g - 2CBUSH

			Analysis Modes					
	Mode #		**1**	**2**	**4**	**3**	**6**	**5**
		Freq (Hz)	79.73	81.98	438.91	168.84	551.26	506.14
Test Modes	**1**	99.48	0.72	0.19				
	2	157.50	0.20	0.62			0.17	0.15
	3	175.00		0.18	0.72			
	4	407.25				0.57	0.42	0.30
	5	445.00				0.16	0.80	0.67
	6	458.13					0.60	0.98



Four CBUSH Isolator FEM

MAC Matrix for Single M6 Isolator 2pt5g - 4CBUSH

			Analysis Modes					
	Mode #		**1**	**3**	**2**	**5**	**4**	**6**
		Freq (Hz)	100.72	125.73	125.08	311.99	277.70	377.14
Test Modes	**1**	99.48	0.80					
	2	157.50	0.27	0.72				
	3	175.00			0.84			
	4	407.25				0.84	0.23	0.30
	5	445.00					0.91	0.66
	6	458.13					0.50	0.96

Four CBUSH FEM Chosen and Used for Rest of Correlation Process

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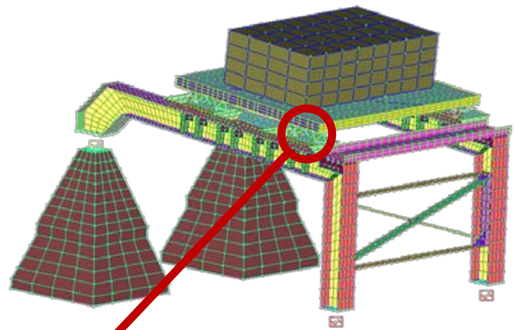
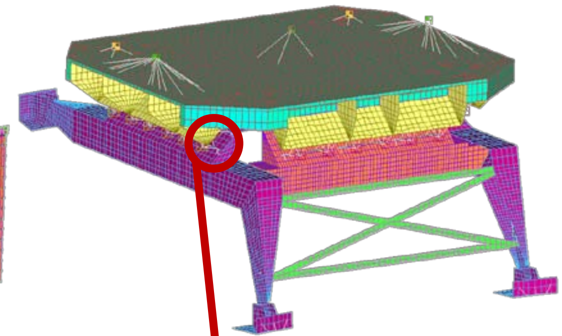
Dynamic Environments Workshop

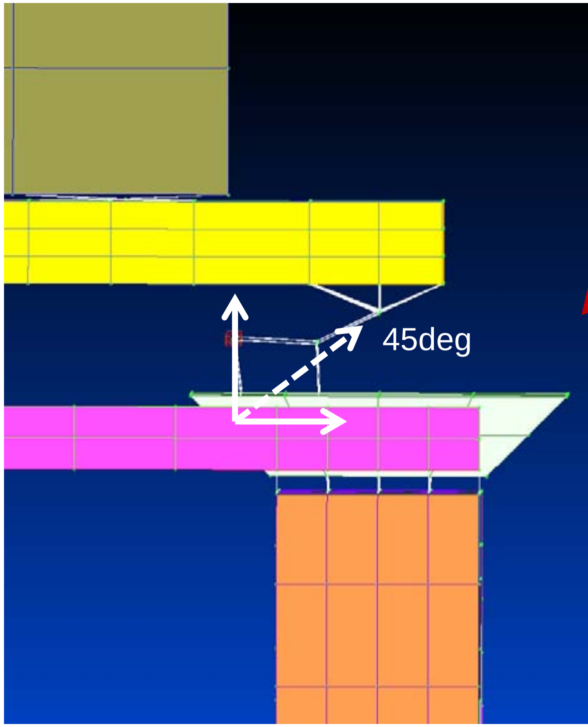
Correlation

Correlation

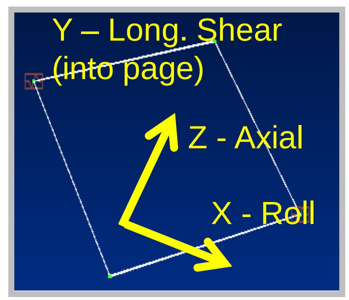
Isolator Orientation



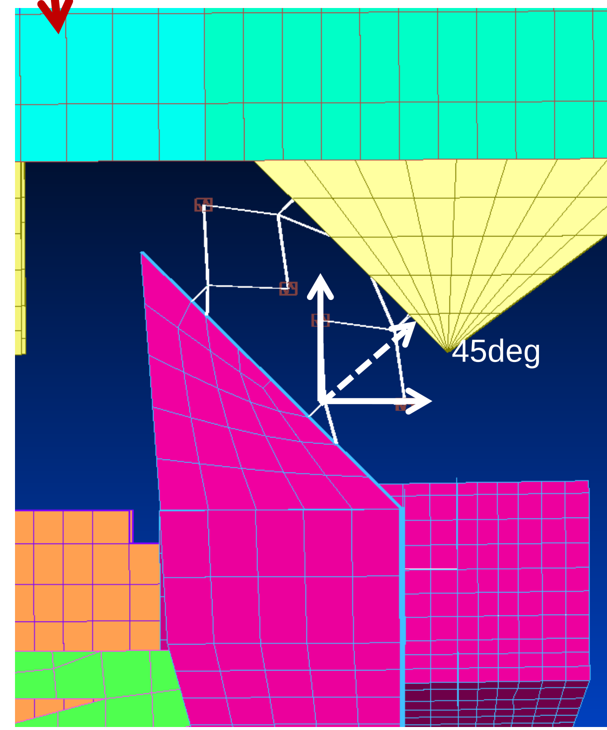




March 2010 Small Pallet



Isolator Local Coordinate System



EFT-1 Pallet

- EFT-1 Pallet isolators are oriented 45deg from the vertical
- Isolator local coordinate system used during correlation
- One configuration considered for correlation effort →
  - *Small Pallet w/ 70lb avionics mass simulator, isolated by 4 M6-120-10 wire ropes*
  - *This configuration most closely matched the EFT-1 Pallet design's isolator orientation*

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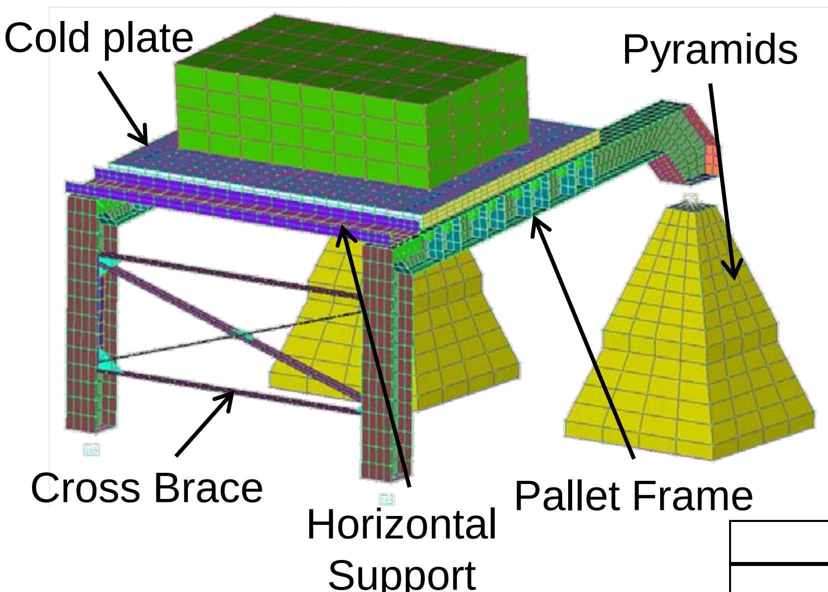
Correlation: Hard Mounted Test Configuration

- Hard mounted configuration was correlated first to ensure proper boundary conditions and pallet structural properties were well correlated
- Young's Modulus, E, of pallet structure parts were allowed to vary +/-10%
- Thickness of cold plate ribs allowed to vary +/- 5% to account for radii
- Largest impact from changes in boundary conditions of pallet legs (rotational stiffness of CBUSH elements at pallet feet) and mass simulator to cold plate RBE connections

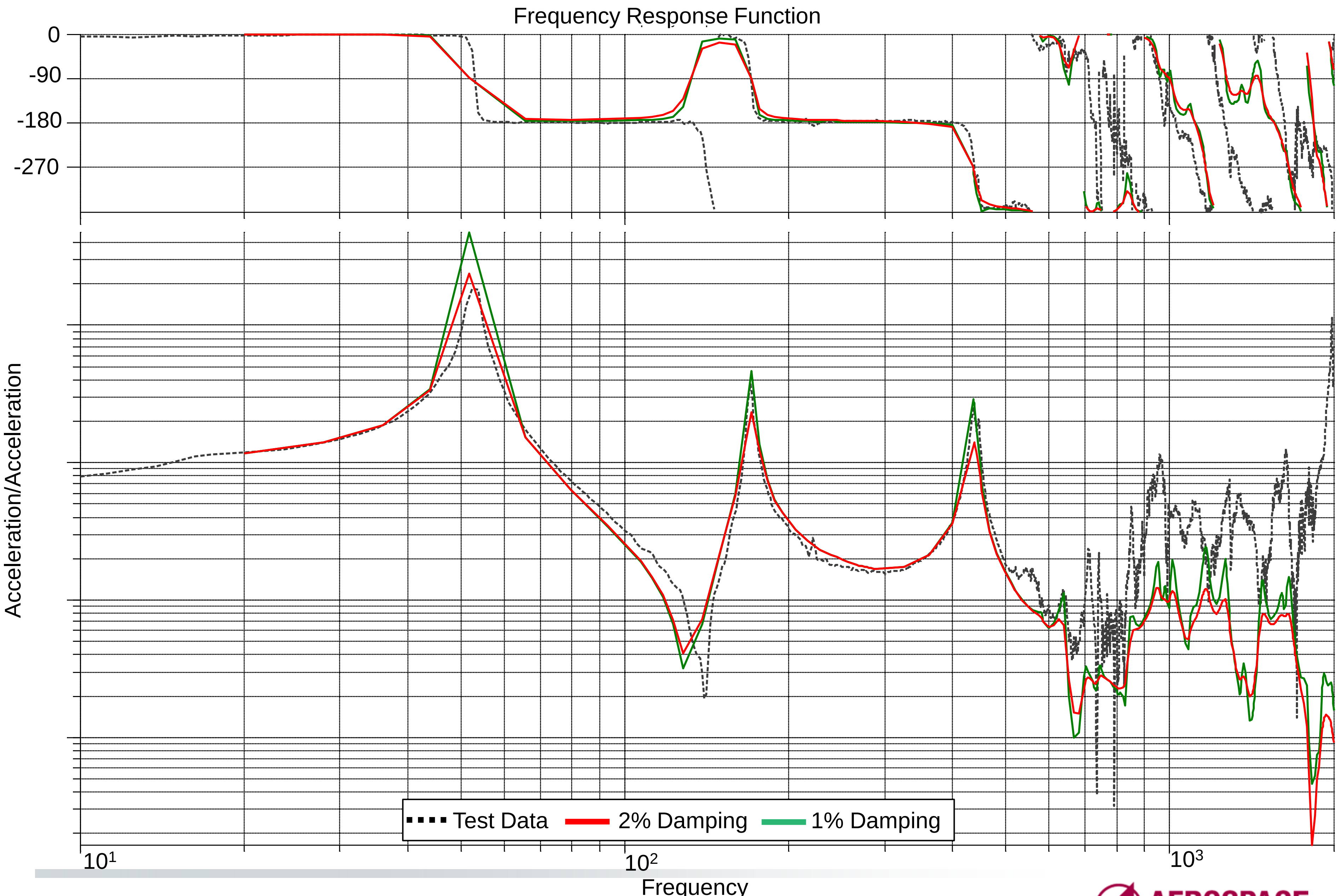


				Design Limits		Set 1	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
13	MA213	Pallet Frame, E	9.90E+06	0.90	1.10	0.99	9.80E+06
14	MA223	Pallet Cross Brace, E	9.90E+06	0.90	1.12	1.10	1.09E+07
15	MA233	Coldplate, E	9.90E+06	0.85	1.12	1.10	1.09E+07
16	MA263	Horizontal Support, E	9.90E+06	0.90	1.10	1.04	1.03E+07
17	MA53	Pyramids, E	9.70E+06	0.90	1.10	0.98	9.51E+06
18	PS324	Coldplate, T	0.125	0.95	1.07	1.05	0.131
19	PS334	Coldplate Outer Rib, T	0.250	0.95	1.05	1.04	0.260
20	PS344	Coldplate Inner Rib, T	0.125	0.95	1.07	1.05	0.131

XORTHO Matrix for Hard Mount Pallet

			Analysis Modes						
	Mode #		**1**	**2**	**3**	**4**	**5**	**6**	Frequency
		Freq (Hz)	52.22	107.96	136.06	171.96	214.93	248.16	% Diff.
Test Modes	**1**	52.94	1.00						-1.37%
	2	108.89		0.99	0.10				-0.85%
	3	136.38			0.97	0.15	0.19	0.15	-0.23%
	4	170.00				0.99			1.16%
	5	222.59				0.15	0.86	0.58	-3.44%
	6	244.63	0.19			0.11	0.25	0.85	1.44%

Test vs. Analysis Mass Simulator FRF Comparison – X (Tangential) Input



SM Small Isolated Pallet Correlation

- ATTUNE v2.1 was used for mode shape and frequency correlation in order to determine isolator stiffness properties
  - *Multiple optimization runs completed for each of the 10 test runs (All XORTHOs in Back-up)*
  - *X (Tangential) (3.65Grms, 7.35Grms, 14.7Grms, 21.9Grms)*
  - *Y (Radial) (3.65Grms, 7.35Grms, 14.7Grms)*
  - *Z (Axial) (5.2Grms, 10.4Grms, 20.8Grms)*
- Frequency response analysis comparisons were used to determine isolator damping properties
  - *Each test run was correlated (frequency/mode shape) which created 10 different FEMs with 10 different sets of isolator properties*
  - *For each of the 10 correlated models, four different damping values were applied during frequency response analyses and compared against the test data → This resulted in stiffness and damping as a function of isolator displacement*
  - *Stiffness/Damping properties showed an "asymptotic" behavior → asymptotic value used in EFT-1 Pallet*
- Isolator displacements recovered in EFT-1 frequency response analyses and compared back to correlated isolator displacement properties to validate isolators were performing/behaving consistently with the correlated results

Correlation: SM Small Pallet Isolated – X (Tangential) Input

XORTHO Matrix for Run83 X 21pt9g						
			Analysis Modes			
	Mode #		**1**	**5**	**7**	Frequency
		Freq (Hz)	19.66	64.00	153.67	Diff %
Test Modes	**1**	19.63	0.99			0.1%
	2	64.38		0.99		-0.6%
	3	168.13			0.96	-8.6%

				Design Limits		Set 4 - X 21.9Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	1.34	348
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	2.16	2376
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	1.27	330
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	2.16	2376
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.02	1.02E+07

Correlation: SM Small Pallet Isolated – Y (Radial) Input

XORTHO Matrix for Run93 Y 14pt7g						
			Analysis Modes			
	Mode #		**2**	**6**	**10**	Frequency
		Freq (Hz)	27.18	74.21	226.49	Diff %
Test Modes	**1**	26.88	1.00			1.1%
	2	75.58		0.94	0.12	-1.8%
	3	227.23			0.98	-0.3%

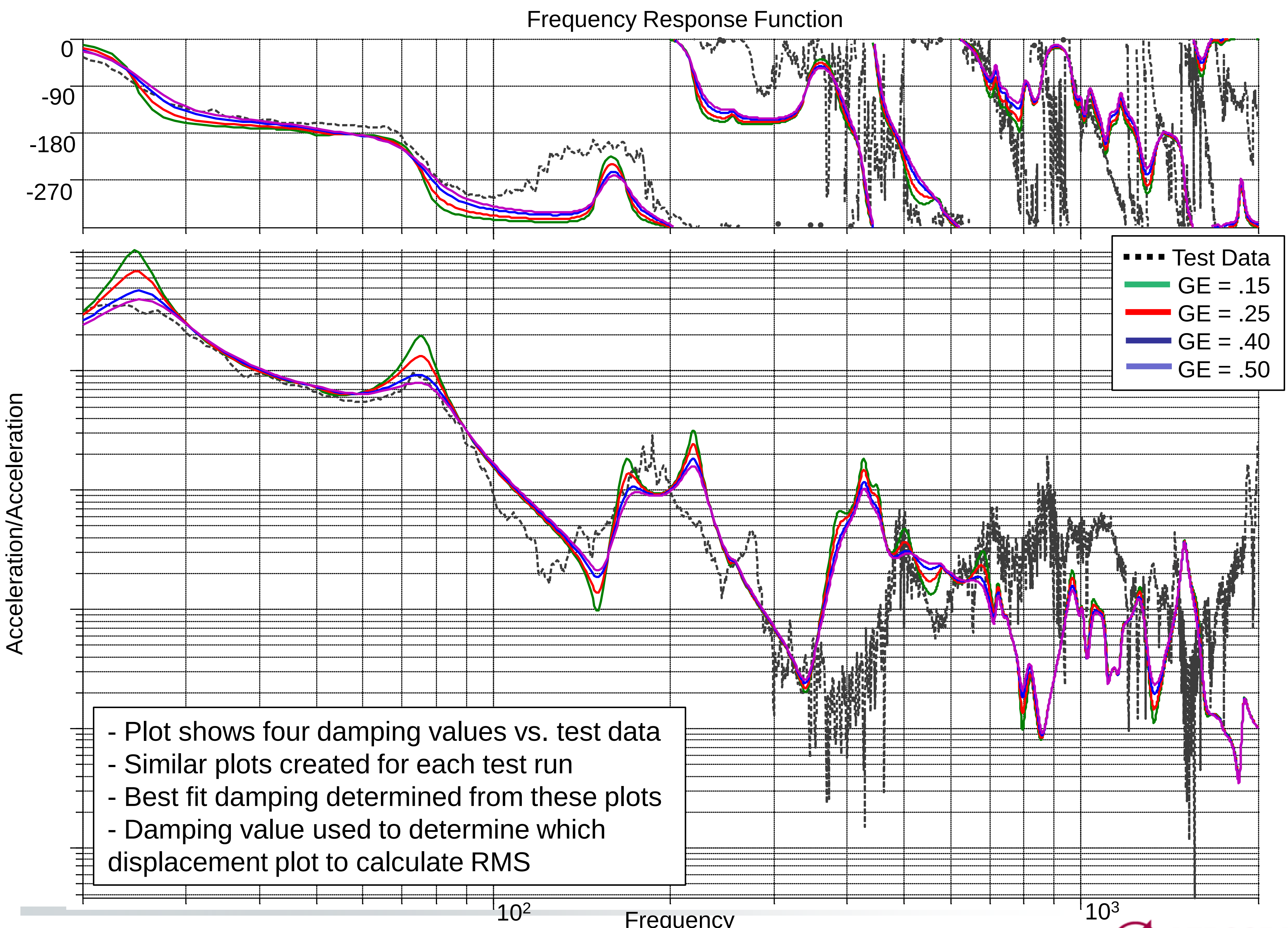
				Design Limits		Set 3 - Y 14.7Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	1.85	481
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.98	515
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	2.52	2772
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	1.85	481
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.94	504
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	2.52	2772
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.09	1.08E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.03	1.03E+07

Correlation: SM Small Pallet Isolated – Z (Axial) Input

XORTHO Matrix for Run125 Z 20pt8g					
			Analysis Modes		
	Mode #		**3**	**10**	Frequency
		Freq (Hz)	31.47	223.54	Diff %
Test Modes	**1**	31.52	0.99		-0.2%
	3	230.17		0.98	-2.9%

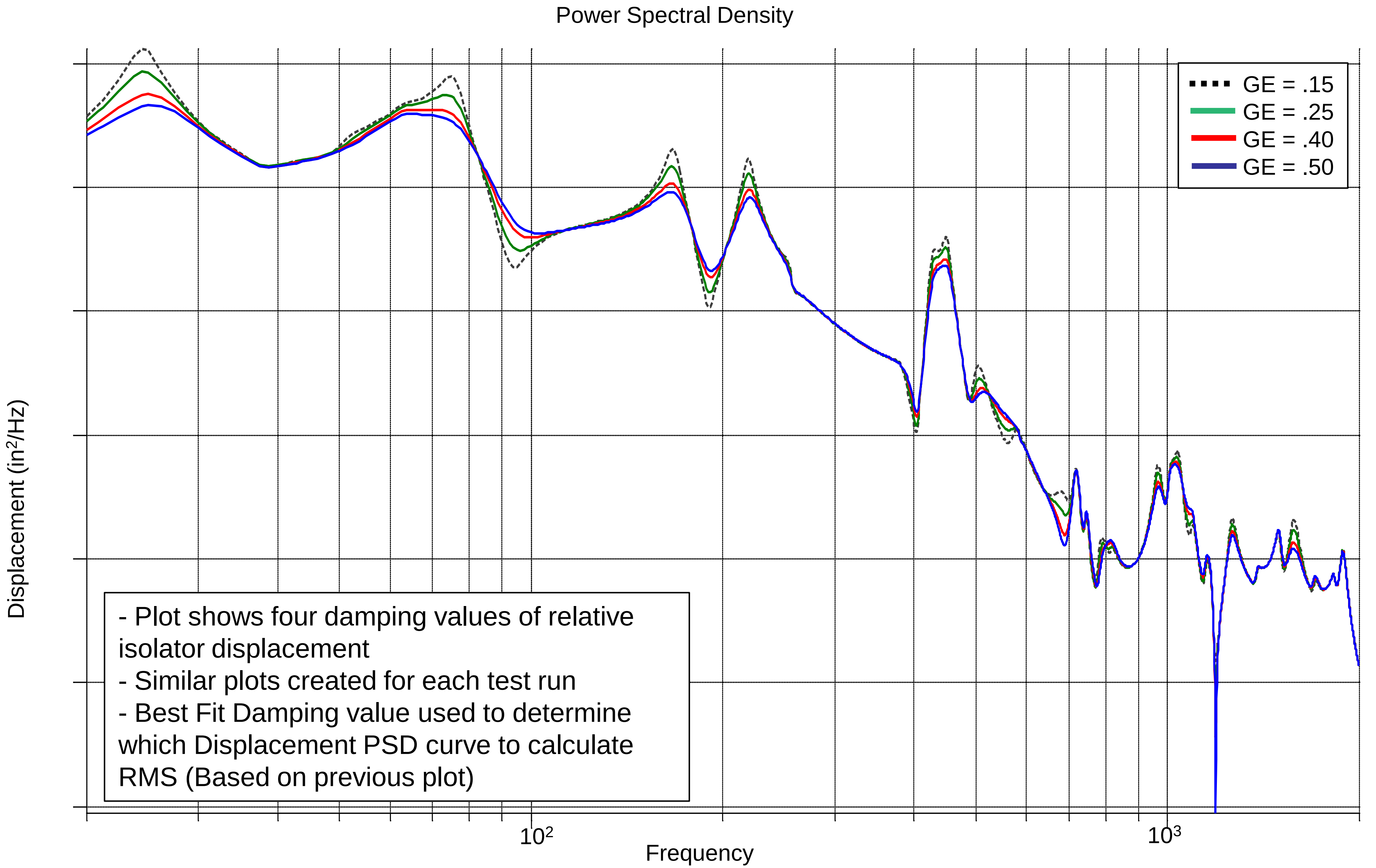
				Design Limits		Set 4 - Z 20.8Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	1.26	328
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.04	270
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	1.26	1386
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	1.26	328
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	1.26	1386
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.04	1.03E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.01	1.01E+07

Test vs. Analysis Damping Comparison – X (Tangential) Axis Mass Simulator



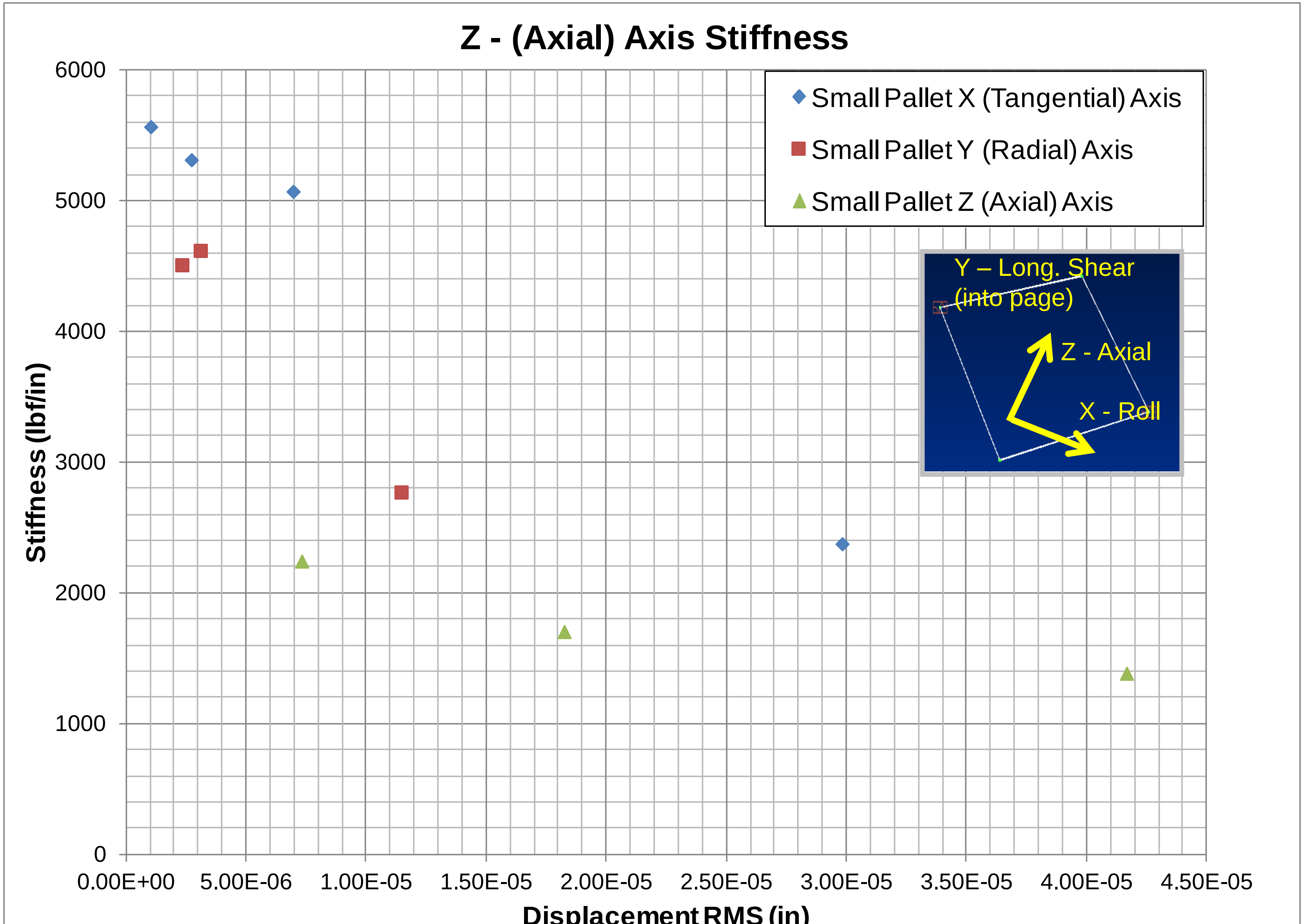
- Plot shows four damping values vs. test data
- Similar plots created for each test run
- Best fit damping determined from these plots
- Damping value used to determine which displacement plot to calculate RMS

Isolator Displacement PSD Comparison – X (Tang.) Axis



- Plot shows four damping values of relative isolator displacement
- Similar plots created for each test run
- Best Fit Damping value used to determine which Displacement PSD curve to calculate RMS (Based on previous plot)

Stiffness vs. Displacement



Downward trend in stiffness as displacement increases → Approaches Manufacturer Spec

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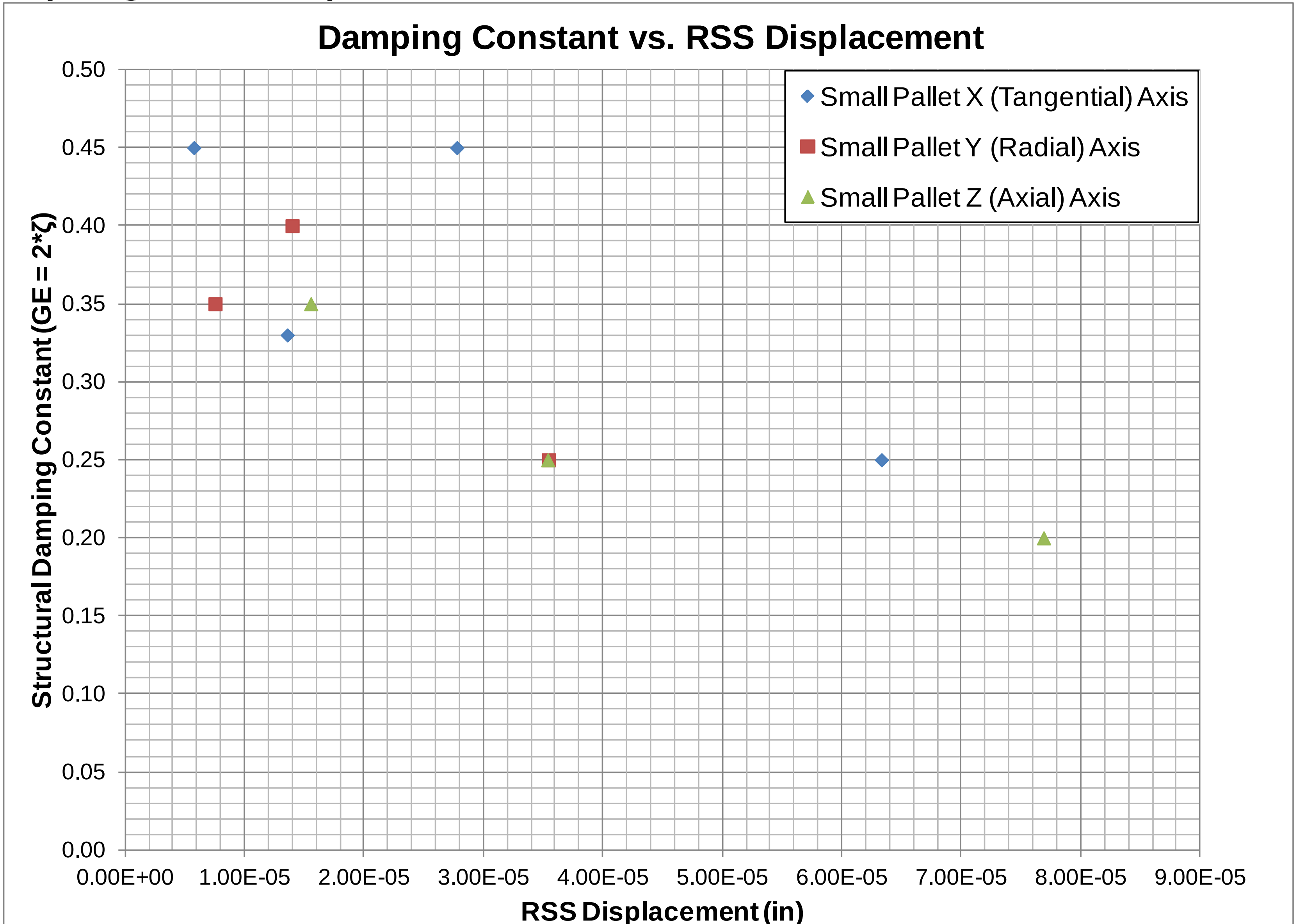
Damping vs. Displacement



Downward trend in damping as displacement increases – not as apparent as stiffness

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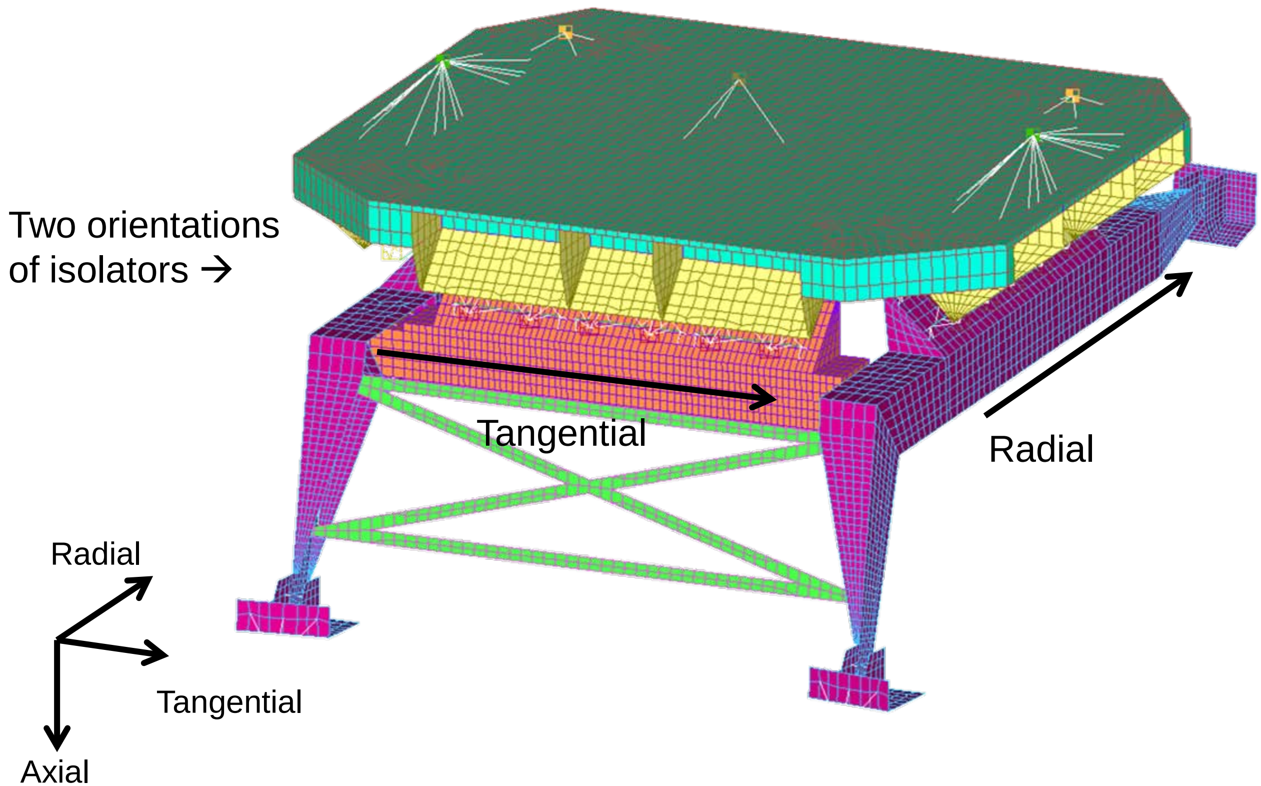
EFT-1 Configuration

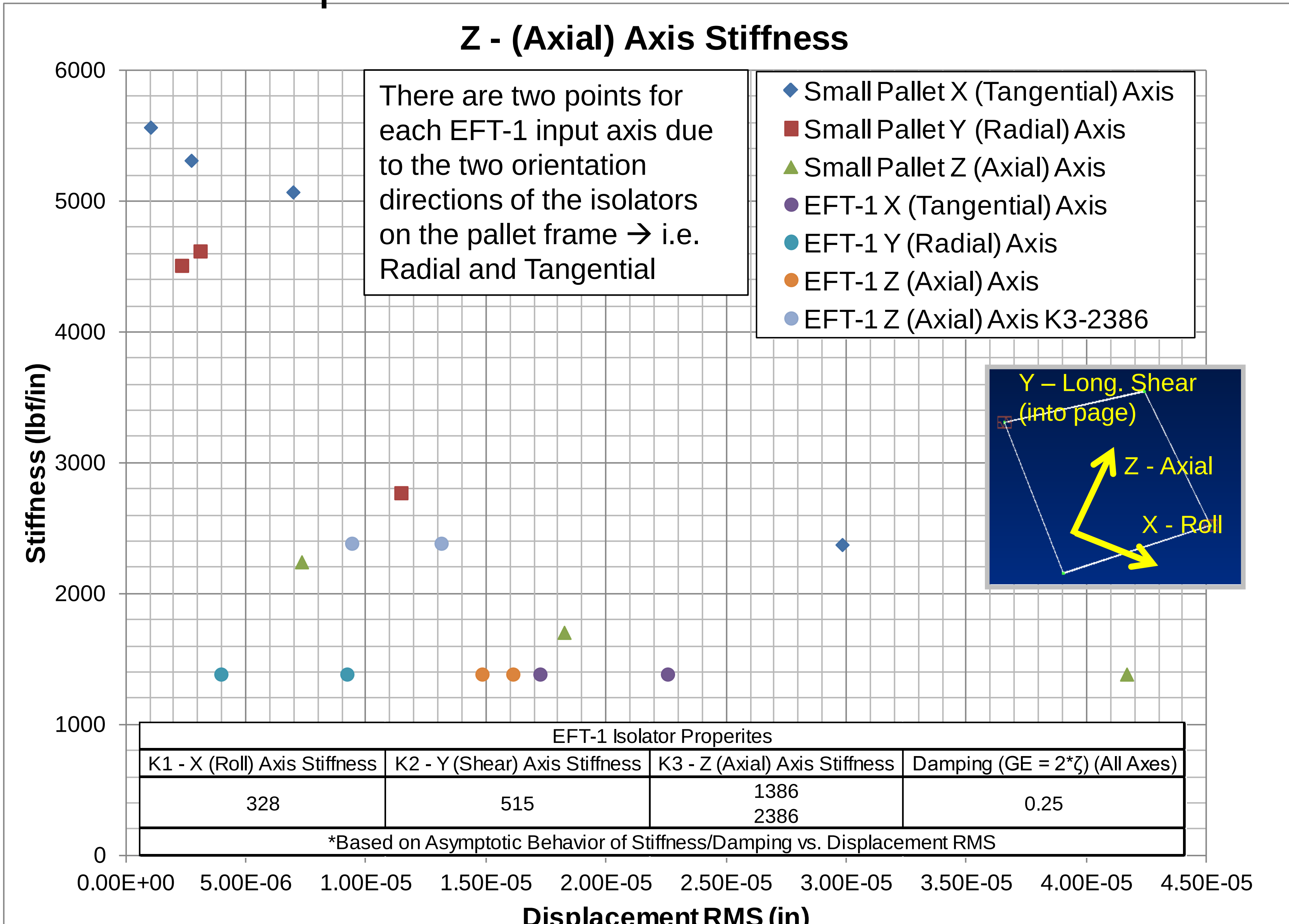
EFT-1 Pallet Configuration



Mass: 185.52 lbs

MODEL SUMMARY	
ENTRY NAME	NUMBER OF ENTRIES
----------	-----------------
CBAR	1028
CBUSH	96
CHEXA	7221
CONM2	5
CORD2C	2
CORD2R	10
CORD2S	1
CPENTA	18
CQUAD4	11016
CTRIA3	188
EIGRL	1
GRID	23098
MAT1	4
MPC	288
MPCADD	1
PARAM	4
PBAR	1
PBARL	1
PBUSH	4
PSHELL	5
PSOLID	1
RBE2	198
RBE3	192

Stiffness vs. Displacement w/ EFT-1 Results



EFT-1 Isolator Properites			
K1 - X (Roll) Axis Stiffness	K2 - Y (Shear) Axis Stiffness	K3 - Z (Axial) Axis Stiffness	Damping (GE = 2*ζ) (All Axes)
328	515	1386 2386	0.25
*Based on Asymptotic Behavior of Stiffness/Damping vs. Displacement RMS			

EFT-1 displacement results initially below correlation results → Axial Stiffness increased

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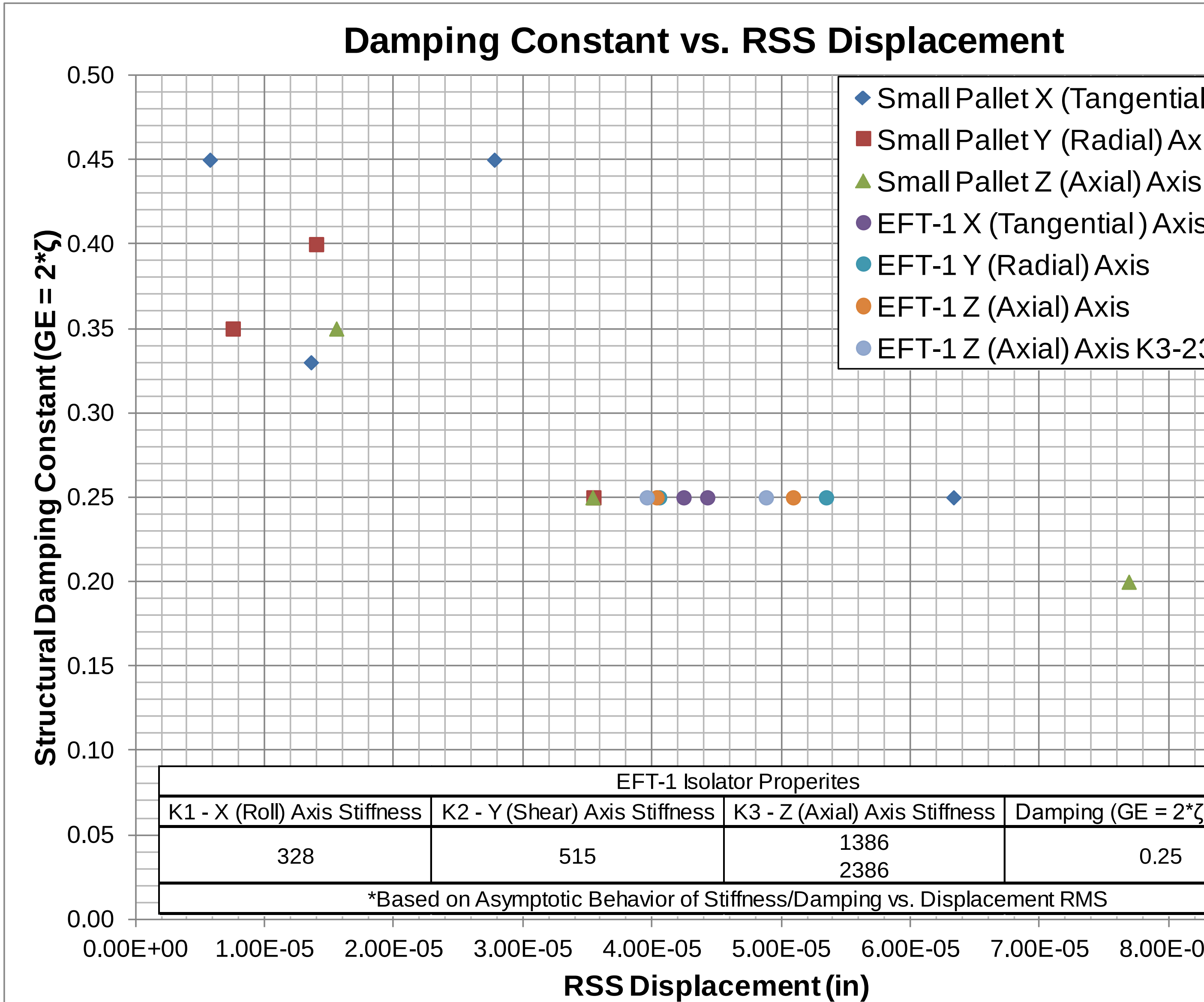
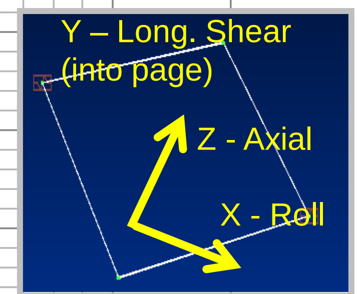
Damping vs. Displacement w/ EFT-1 Results



EFT-1 Isolator Properites			
K1 - X (Roll) Axis Stiffness	K2 - Y (Shear) Axis Stiffness	K3 - Z (Axial) Axis Stiffness	Damping (GE = 2*ζ) (All Axes)
328	515	1386 2386	0.25
*Based on Asymptotic Behavior of Stiffness/Damping vs. Displacement RMS			



EFT-1 displacements lie within the correlation results

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Conclusion

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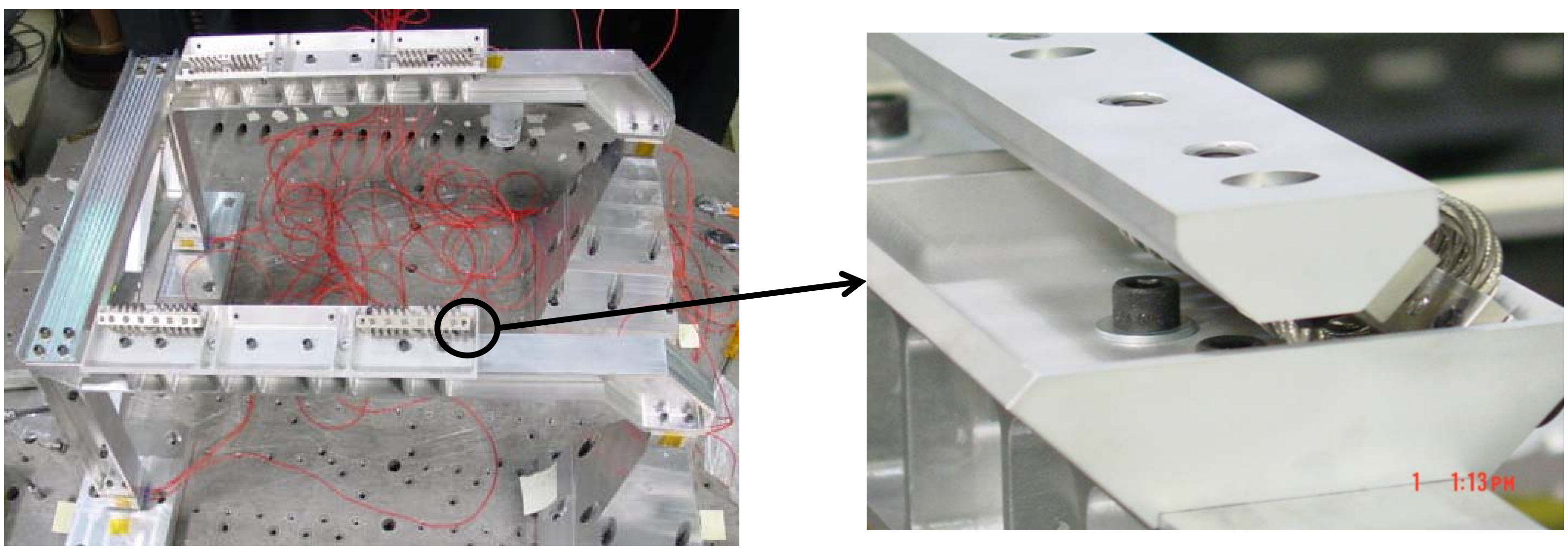
Conclusions

- March 2010 pallet development test proved feasibility of wire rope isolators
- Wire rope isolator properties developed as a function of isolator displacement
- Stepping block approach for correlation (hard mount pallet correlation, single isolator test, followed by isolated pallet correlation) was necessary to produce valid results
- Test data shows wire rope isolators soften as input level (relative displacement of isolator) increases
- Correlated analysis results illustrate same softening characteristics as test data
- Correlated isolator properties along with EFT-1 FEM will be used to develop more accurate/less conservative avionics component flight environments
  - *Caution must still be used (vary stiffness/damping to account for scatter and uncertainties) as no testing is planned for the EFT-1 isolated pallet design*



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- Lee Philley – NASA JSC

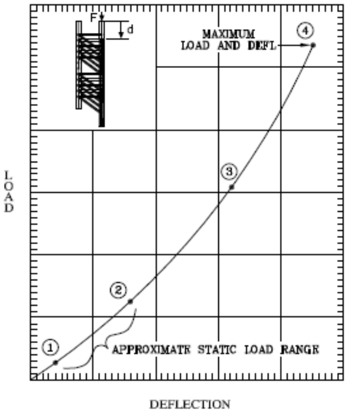
Thank you

Spacecraft and Launch Vehicle Dynamic Environments Workshop

BACK UP CHARTS

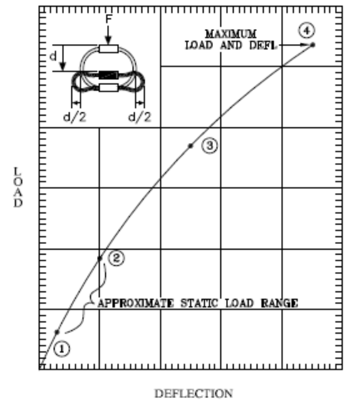
M6-120-100 Manufacturer Spec

SHEAR



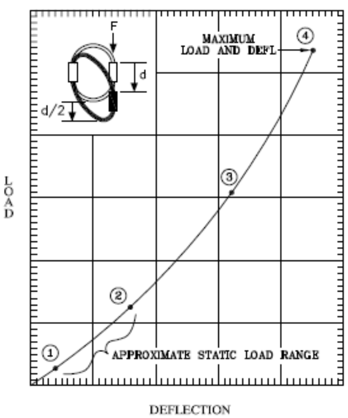
PART NO.	①		②		③		④		K_v	K_s
	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	(VIBR) (lbs/in)	(SHOCK) (lbs/in)
M6–120–10	52	.05	123	.10	230	.18	625	.35	1040	1280
M6–130–10	40	.05	93	.10	190	.22	490	.45	800	870
M6–140–10	31	.05	72	.10	175	.28	465	.55	620	640
M6–150–10	24	.05	53	.10	145	.35	390	.70	480	500
M6–160–10	17	.05	40	.10	140	.40	370	.80	340	360
M6–170–10	14	.05	33	.10	120	.45	335	.90	280	300

COMPRESSION



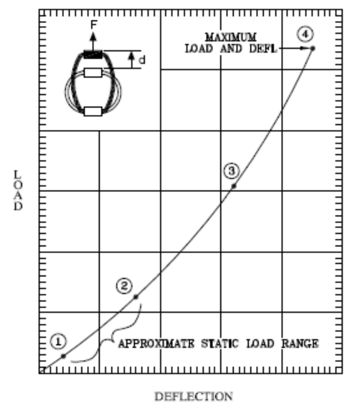
PART NO.	①		②		③		④		K_v	K_s
	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	(VIBR) (lbs/in)	(SHOCK) (lbs/in)
M6–120–10	210	.05	370	.10	580	.18	750	.35	4200	3200
M6–130–10	160	.05	280	.10	470	.22	610	.45	3200	2150
M6–140–10	125	.05	215	.10	440	.28	580	.55	2500	1575
M6–150–10	95	.05	160	.10	360	.35	490	.70	1900	1025
M6–160–10	70	.05	120	.10	350	.40	460	.80	1400	875
M6–170–10	55	.05	100	.10	300	.45	420	.90	1100	675

ROLL



PART NO.	①		②		③		④		K_v	K_s
	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	(VIBR) (lbs/in)	(SHOCK) (lbs/in)
M6–120–10	52	.05	123	.10	230	.18	625	.35	1040	1280
M6–130–10	40	.05	93	.10	190	.22	490	.45	800	870
M6–140–10	31	.05	72	.10	175	.28	465	.55	620	640
M6–150–10	24	.05	53	.10	145	.35	390	.70	480	500
M6–160–10	17	.05	40	.10	140	.40	370	.80	340	360
M6–170–10	14	.05	33	.10	120	.45	335	.90	280	300

TENSION



PART NO.	①		②		③		④		K_v	K_s
	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	LOAD (lbs)	DEFL (in)	(VIBR) (lbs/in)	(SHOCK) (lbs/in)
M6–120–10	230	.05	520	.10	950	.15	1740	.20	4600	6330
M6–130–10	180	.05	390	.10	700	.15	1400	.25	3600	4670
M6–140–10	140	.05	300	.10	530	.15	1320	.30	2800	3530
M6–150–10	105	.05	225	.10	440	.18	1080	.35	2100	2420
M6–160–10	75	.05	170	.10	420	.20	1050	.40	1500	2100
M6–170–10	60	.05	140	.10	360	.23	900	.45	1200	1570

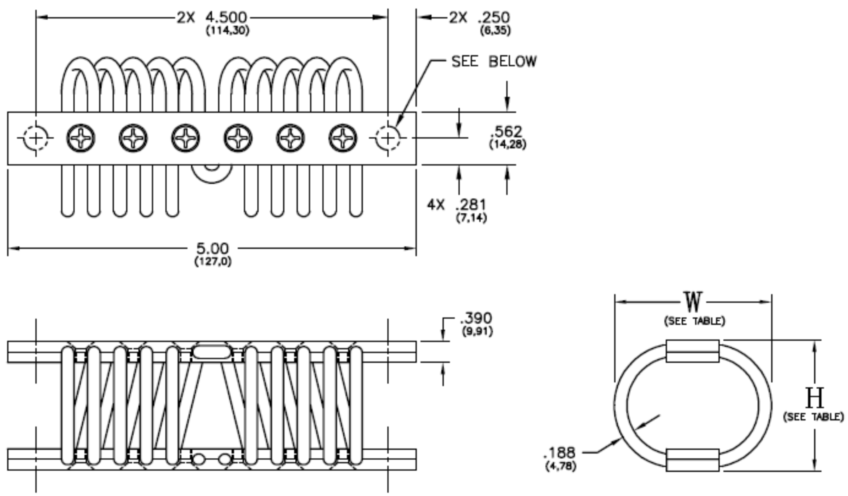
ULTIMATE BREAKING STRENGTH –3k lbs

-Local coordinate systems used lined up with the shear, roll and compression stiffness values provided by the manufacturer
- Tension and Compression values averaged
-DATA from www.isolator.com (Isolation Dynamics Corp.)

AEROSPACE

M6-120-10 Design Data

DESIGN DATA • **M6** SERIES SHOCK & VIBRATION ISOLATORS • 3/16" DIAMETER CABLE



FEATURES:

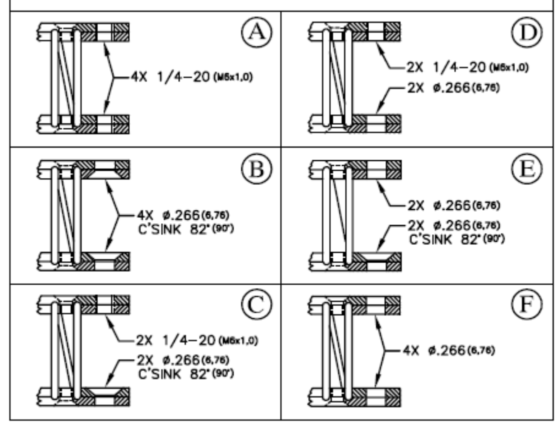
- RUGGED ALL METAL CONSTRUCTION
- UNEQUALLED TEMP. RANGE: −200°F TO 500°F
- THREE AXIS CAPABILITY
- MAINTENANCE FREE
- FAIL SAFE DESIGN
- HIGH DAMPING: C/Cc ≃ .20
- EXCEPTIONAL RELIABILITY AND LONG LIFE

MATERIALS/FINISHES:

- CABLE: 300 SERIES SS PER MIL−W−83420 OR RR−W−410
- SCREWS: 300 SERIES SS PER MS51959−28
- INSERTS: 300 SERIES SS (ALUM BARS ONLY)
- RETAINER BARS: SEE BELOW

PART NUMBER	DIMENSIONS, in. H ±.03	DIMENSIONS, in. W (REF)	ISOLATOR WEIGHT (SEE NOTE 3)
M6 – 120 – 10 – [ ]	1.20 (30,5)	1.40 (35,6)	.42lbs (.19kg)
M6 – 130 – 10 – [ ]	1.30 (33,0)	1.50 (38,1)	.44lbs (.20kg)
M6 – 140 – 10 – [ ]	1.40 (35,6)	1.60 (40,6)	.46lbs (.21kg)
M6 – 150 – 10 – [ ]	1.50 (38,1)	1.70 (43,2)	.47lbs (.21kg)
M6 – 160 – 10 – [ ]	1.60 (40,6)	1.80 (45,7)	.49lbs (.22kg)
M6 – 170 – 10 – [ ]	1.70 (43,2)	1.90 (48,2)	.51lbs (.23kg)

MOUNTING HOLE OPTIONS



SM Avionics Pallet Test Levels

- Unit under test was exposed to three distinct ‘g’ levels in each axis
- The FRF data acquired during testing showed increased distortion (high damping and softening characteristics) as input level was increased → wire rope isolators are known to behave non-linearly

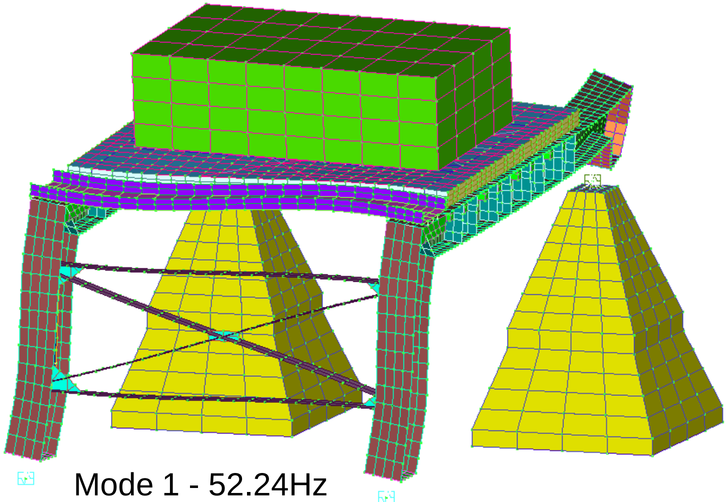
Small Pallet						
	Tangential (X Axis)		Radial (Yaxis)		Axial (Z Axis)	
Set	Grms Level	Test Run	Grms Level	Test Run	Grms Level	Test Run
1	3.65	Run83 18dB Down	3.65	Run91 6dB Down	5.2	Run125 12 dB Down
2	7.35	Run83 12dB Down	7.35	Run91 0 dB Down	10.4	Run125 6 dB Down
3	14.6	Run83 6dB Down	14.7	Run93 0 dB Down	N/A	N/A
4	21.9	Run84 3dB Down	N/A	N/A	20.8	Run125 0 dB Down

SM Pallet Hard Mounted

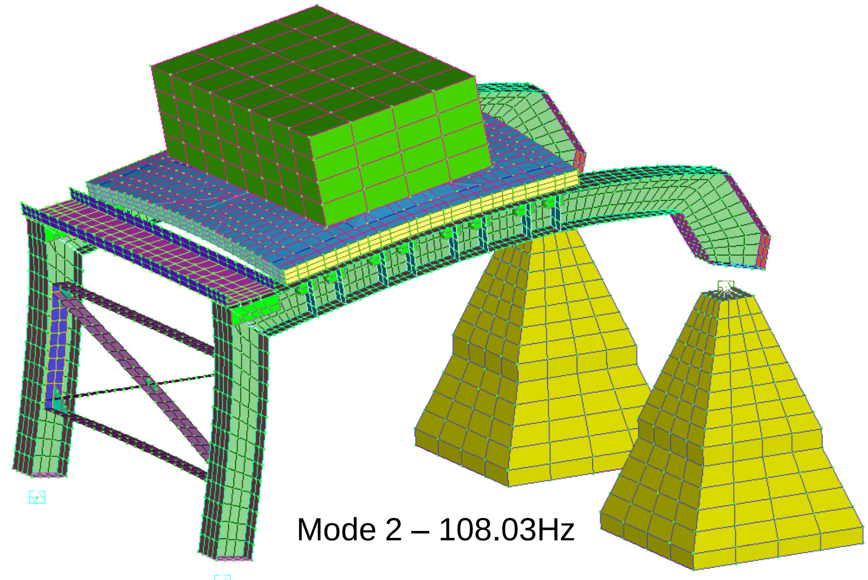
Modal Effective Mass Table

SM Pallet Hard Mounted								
MODE	FREQ	T1 Tangential	T2 Radial	T3 Axial	R1	R2	R3	Mode Description
NO.	Hz	FRAC	FRAC	FRAC	FRAC	FRAC	FRAC	
1	**52.24**	0.47	0.00	0.00	0.00	0.69	0.10	
2	**108.03**	0.00	0.12	0.31	0.00	0.00	0.00	
3	**136.31**	0.00	0.33	0.06	0.31	0.00	0.00	
4	172.03	0.01	0.00	0.00	0.00	0.00	0.02	
5	**215.44**	0.00	0.03	0.05	0.01	0.00	0.00	
6	248.47	0.00	0.00	0.00	0.00	0.04	0.02	
7	264.80	0.00	0.00	0.00	0.00	0.00	0.00	
8	290.26	0.00	0.00	0.00	0.00	0.00	0.00	
9	292.65	0.00	0.00	0.00	0.00	0.00	0.00	
10	298.03	0.00	0.00	0.00	0.00	0.00	0.00	
11	440.62	0.01	0.00	0.00	0.00	0.00	0.00	
12	440.83	0.00	0.00	0.00	0.00	0.00	0.00	
13	454.81	0.00	0.00	0.00	0.00	0.00	0.00	
14	514.68	0.00	0.00	0.00	0.00	0.00	0.00	
15	545.58	0.00	0.00	0.00	0.00	0.00	0.00	
16	605.12	0.00	0.00	0.00	0.00	0.00	0.00	
17	617.16	0.00	0.00	0.00	0.00	0.00	0.00	
18	626.55	0.00	0.01	0.01	0.01	0.00	0.00	
19	681.73	0.00	0.00	0.00	0.00	0.00	0.00	
20	703.54	0.00	0.00	0.00	0.00	0.00	0.00	
SUM MEF		0.49	0.49	0.44	0.34	0.74	0.15	

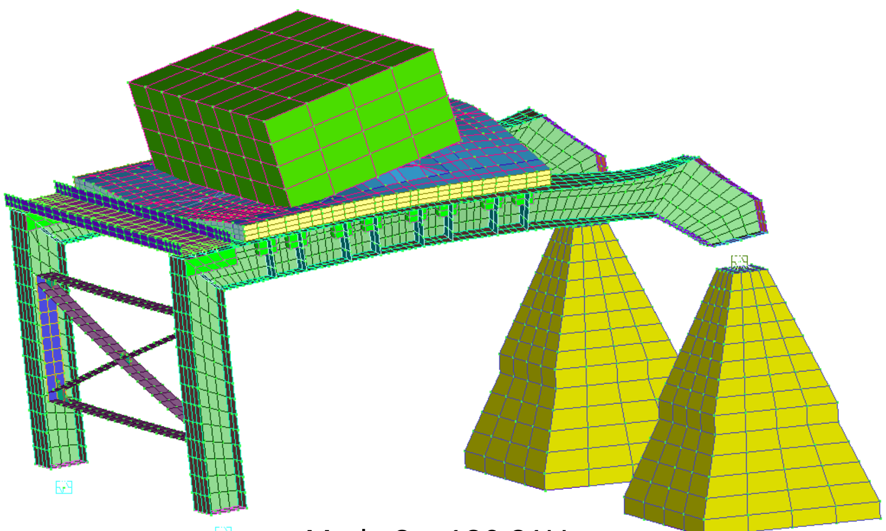
Hard Mounted Mode Shapes



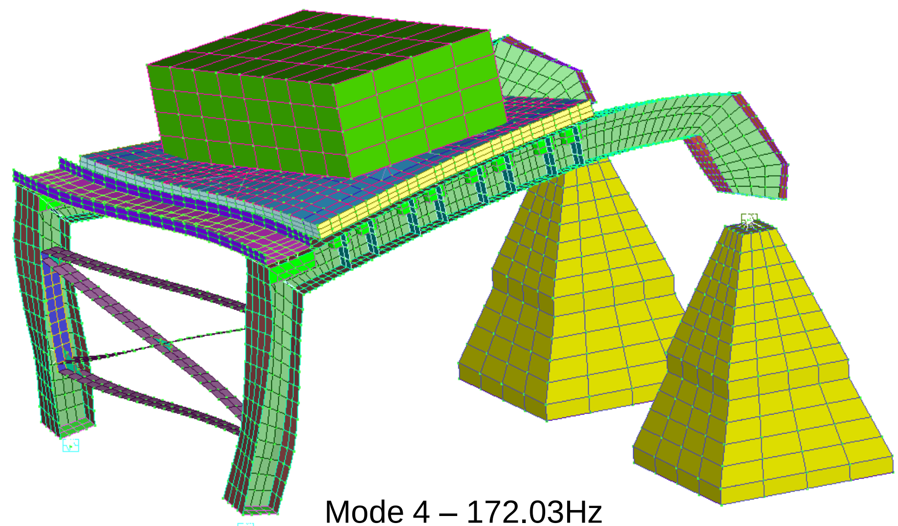
Mode 1 - 52.24Hz



Mode 2 – 108.03Hz



Mode 3 – 136.31Hz



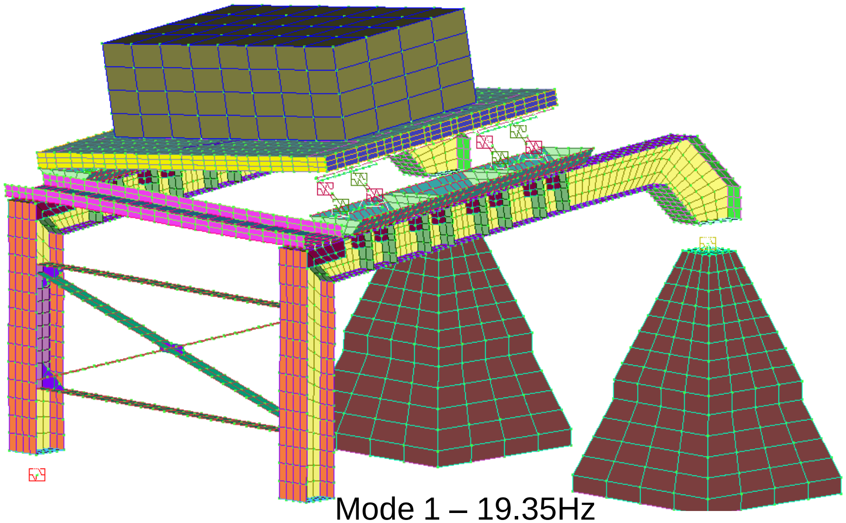
Mode 4 – 172.03Hz

SM Pallet Isolated

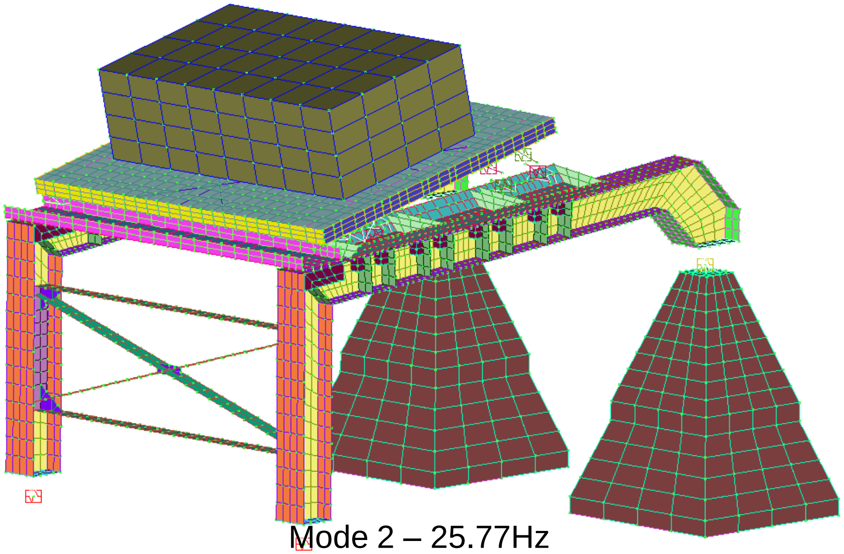
Modal Effective Mass Table – Using Asymptotic Stiffness Values from Displacement vs. Stiffness Curves

Small Pallet - Asymptotic Stiffness									
MODE	FREQ	T1 Tangential	T2 Radial	T3 Axial	R1	R2	R3	Mode Description
NO.	Hz	FRAC	FRAC	FRAC	FRAC	FRAC	FRAC	
1	**19.35**	0.38	0.00	0.00	0.00	0.71	0.08	Tang. Isolation Mode
2	**25.77**	0.00	0.37	0.00	0.29	0.00	0.00	Radial Isolation Mode
3	**31.62**	0.00	0.00	0.40	0.04	0.00	0.00	Axial Isolation Mode
4	**49.32**	0.01	0.00	0.00	0.00	0.00	0.04	Torsion Mode
5	57.66	0.06	0.00	0.00	0.00	0.01	0.00	
6	61.78	0.00	0.03	0.00	0.00	0.00	0.00	
7	**144.92**	0.04	0.00	0.00	0.00	0.05	0.01	Pallet Frame
8	154.30	0.00	0.00	0.00	0.00	0.00	0.00	
9	205.32	0.01	0.00	0.00	0.00	0.00	0.01	
10	225.37	0.00	0.07	0.01	0.01	0.00	0.00	
11	254.17	0.00	0.00	0.00	0.00	0.00	0.00	
12	261.25	0.00	0.00	0.00	0.00	0.00	0.00	
13	275.77	0.00	0.00	0.00	0.00	0.00	0.00	
14	277.99	0.00	0.00	0.00	0.00	0.00	0.00	
15	302.92	0.00	0.00	0.01	0.00	0.00	0.00	
16	315.35	0.00	0.00	0.00	0.00	0.00	0.00	
17	320.80	0.00	0.00	0.00	0.00	0.00	0.00	
18	402.62	0.00	0.00	0.00	0.00	0.00	0.00	
19	406.30	0.00	0.00	0.00	0.00	0.00	0.00	
20	431.61	0.01	0.00	0.00	0.00	0.00	0.00	
SUM MEF		0.51	0.48	0.43	0.35	0.77	0.15	

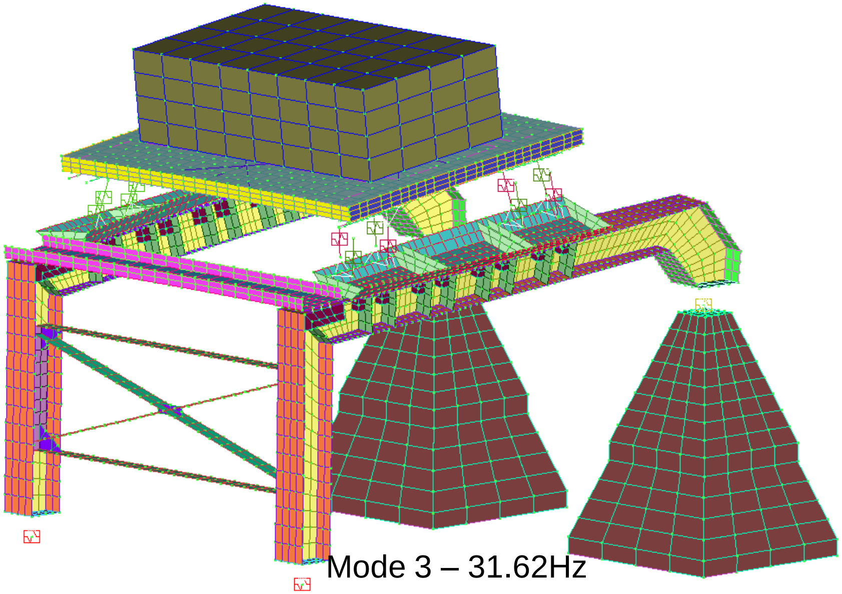
SM Pallet Isolated Mode Shapes (1)



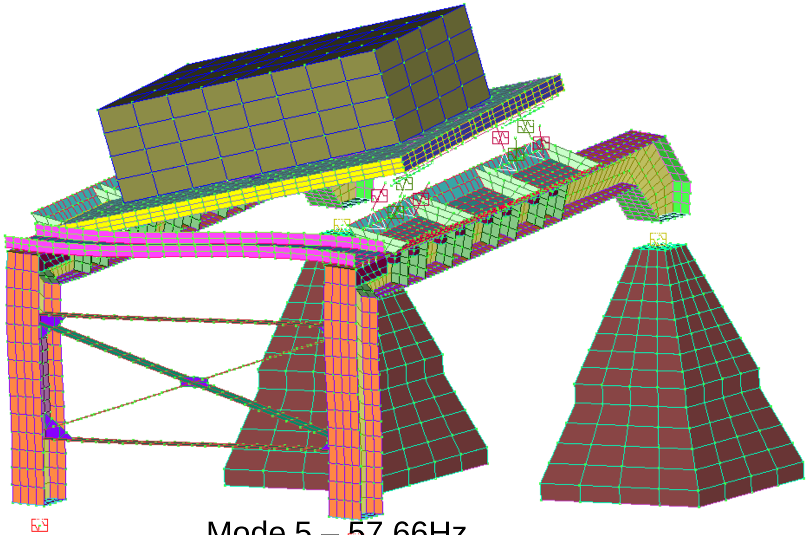
Mode 1 – 19.35Hz



Mode 2 – 25.77Hz

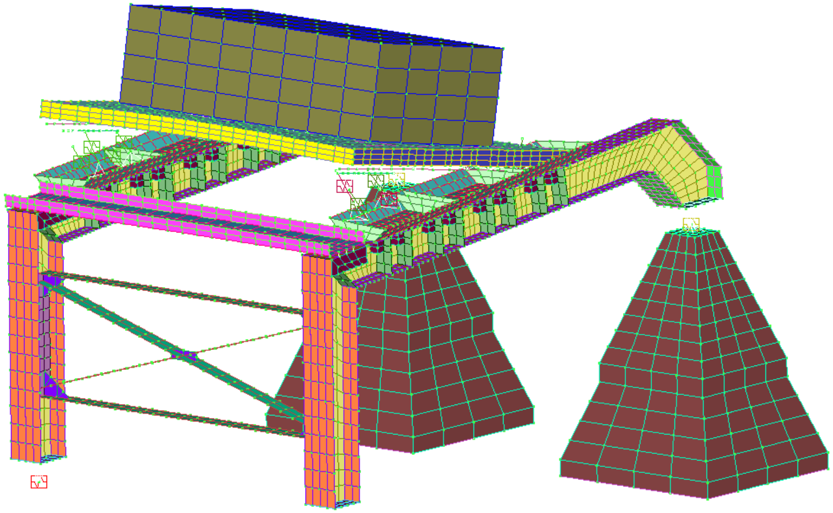


Mode 3 – 31.62Hz

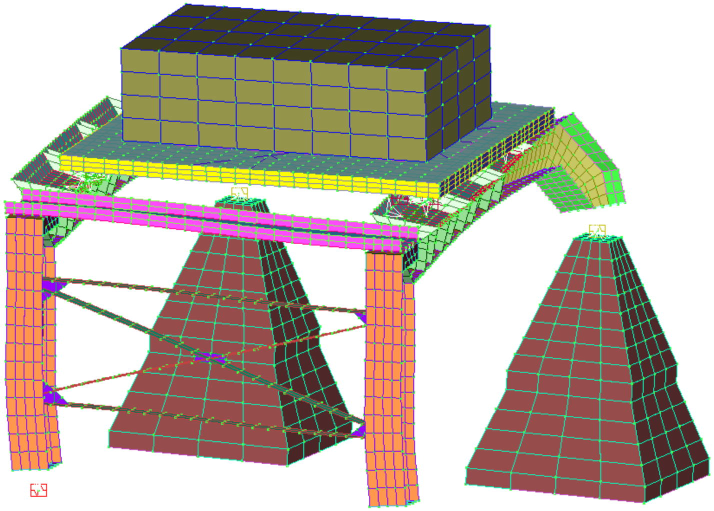


Mode 5 – 57.66Hz

SM Pallet Isolated Mode Shapes (2)



Mode 6 – 61.78Hz



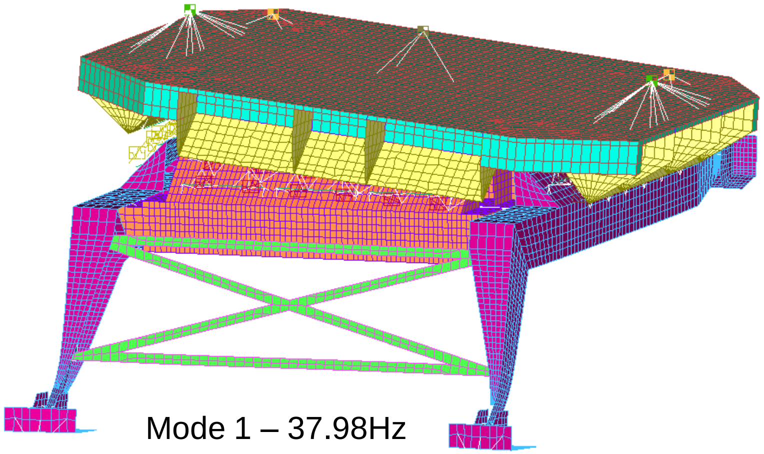
Mode 7 – 144.92Hz

EFT-1 Pallet

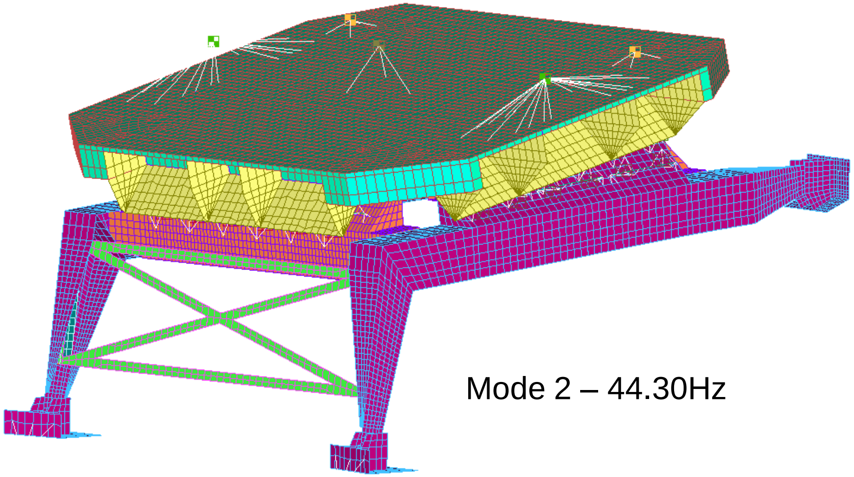
Modal Effective Mass Table

OFT1 Pallet - Correlated Results								
MODE	FREQ	T1 Tangential	T2 Radial	T3 Axial	R1	R2	R3	Mode Description
NO.	Hz	FRAC	FRAC	FRAC	FRAC	FRAC	FRAC	
1	**37.98**	0.00	0.72	0.06	0.76	0.06	0.71	
2	**44.30**	0.00	0.05	0.59	0.00	0.57	0.05	
3	**59.70**	0.83	0.00	0.00	0.00	0.01	0.00	
4	69.13	0.00	0.00	0.00	0.01	0.00	0.00	
5	**75.02**	0.00	0.13	0.02	0.15	0.02	0.14	
6	**104.89**	0.00	0.01	0.14	0.00	0.14	0.01	
7	135.60	0.00	0.00	0.01	0.00	0.01	0.00	
8	172.72	0.00	0.04	0.00	0.04	0.00	0.05	
9	200.18	0.00	0.00	0.00	0.00	0.00	0.00	
10	208.93	0.01	0.00	0.00	0.00	0.00	0.00	
11	217.85	0.00	0.00	0.00	0.00	0.00	0.00	
12	257.78	0.00	0.01	0.00	0.02	0.00	0.01	
13	270.43	0.00	0.00	0.00	0.00	0.00	0.00	
14	292.60	0.00	0.00	0.00	0.00	0.00	0.00	
15	**295.24**	0.07	0.00	0.02	0.00	0.01	0.00	
16	372.43	0.00	0.00	0.00	0.00	0.00	0.00	
17	384.56	0.00	0.00	0.00	0.00	0.00	0.00	
18	393.98	0.00	0.00	0.05	0.00	0.05	0.00	
19	408.40	0.00	0.00	0.00	0.00	0.00	0.00	
20	415.73	0.00	0.00	0.00	0.00	0.00	0.00	
SUM MEF		0.92	0.98	0.88	0.99	0.87	0.98	

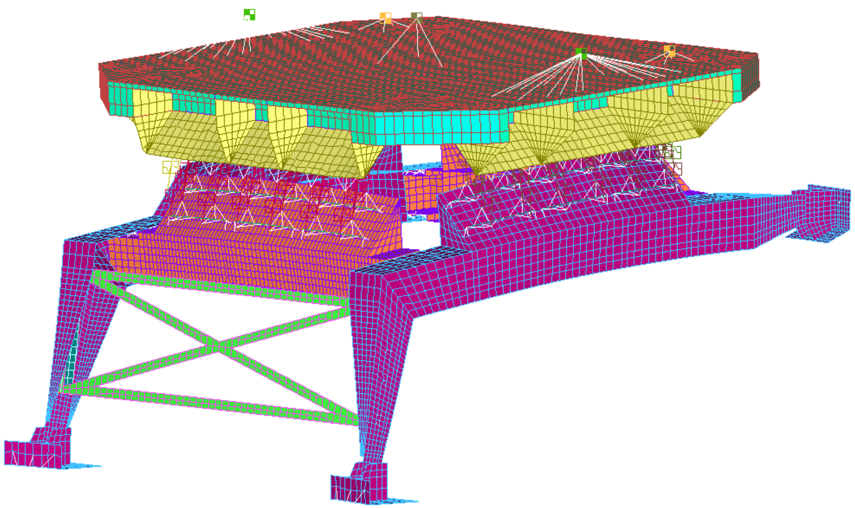
EFT-1 Pallet Mode Shapes(1)



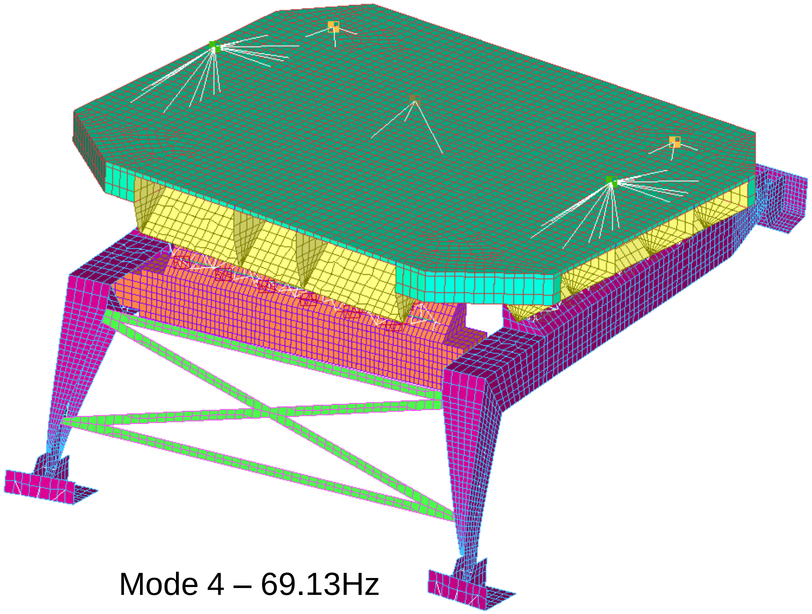
Mode 1 – 37.98Hz



Mode 2 – 44.30Hz

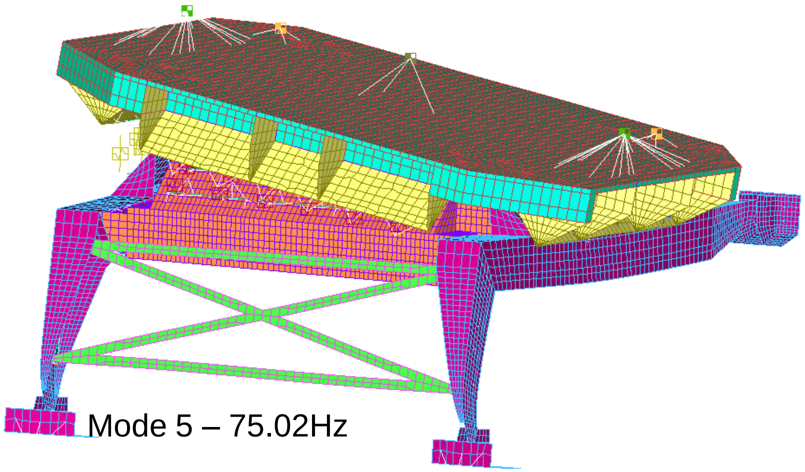


Mode 3 – 59.70Hz

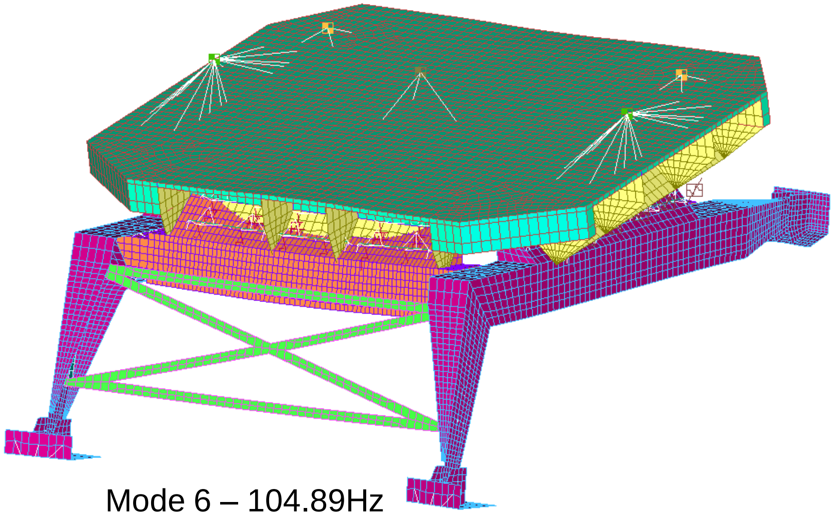


Mode 4 – 69.13Hz

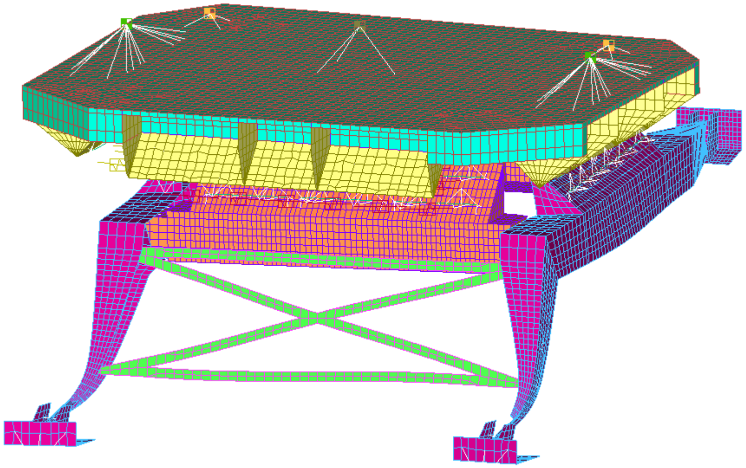
EFT-1 Pallet Mode Shapes(2)



Mode 5 – 75.02Hz



Mode 6 – 104.89Hz



Mode 8 – 172.72Hz

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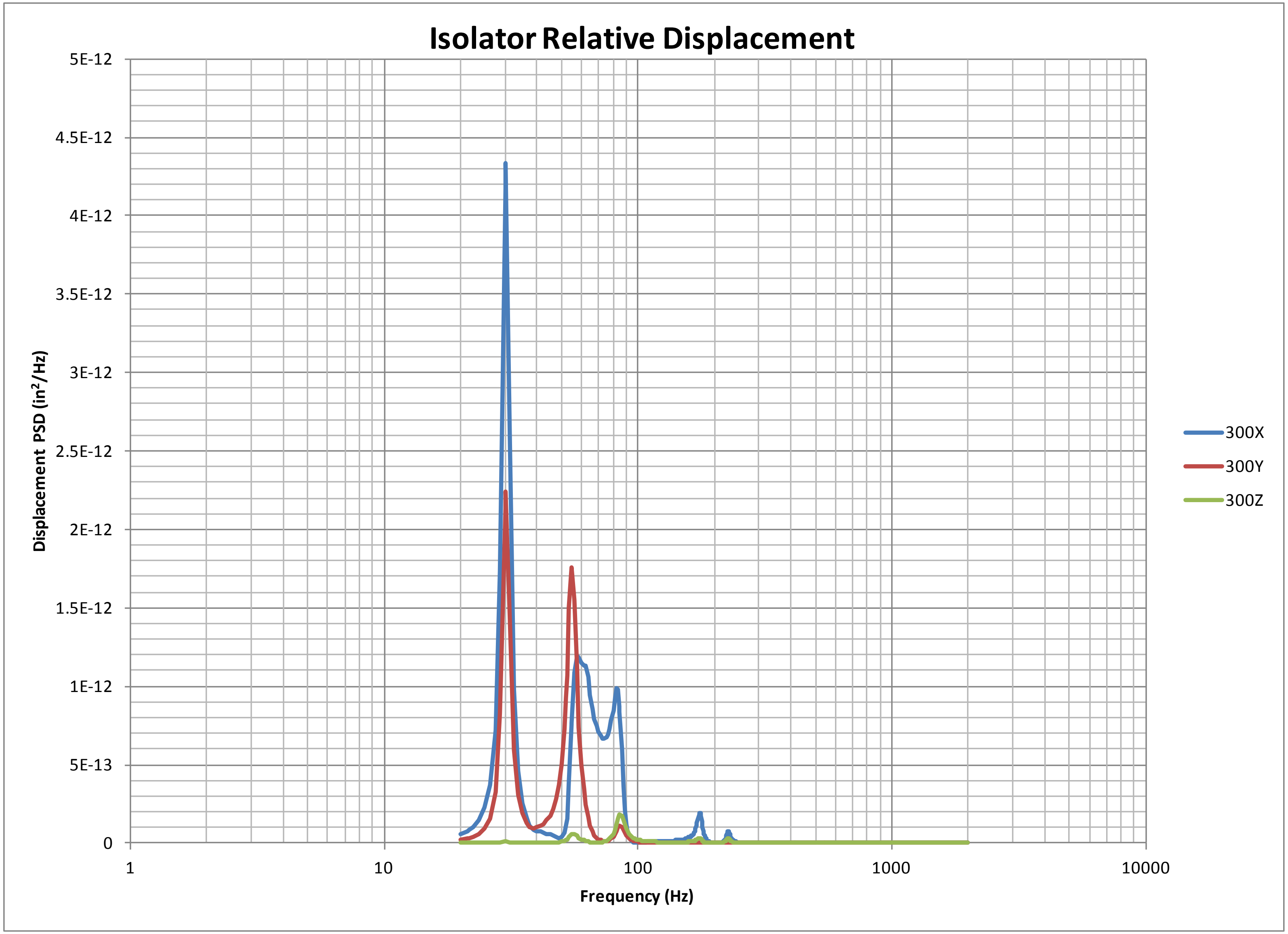
Correlation (6)

Isolator Displacement

- MPC relationship created to determine relative displacement of the isolator CBUSH elements → this node was recovered in the analysis runs
- FRF plots of the Analysis FEM (with 4 different Damping Constants) overlaid with the test data → first mode was used to fit the best damping constant value
- Using the "best fit damping value" the Displacement RMS was calculated from the relative displacement node in the MPC relationship in each response axis → The displacement RMS was calculated from 0-100Hz (See Plots on Next Page)
- In the cases where an in-between damping value was needed the displacement RMS values from two different runs (i.e. two different damping values) were averaged
- The stiffness values found during the ATTUNE FEM correlation process were plotted vs. the displacement RMS values calculated above
- Damping values determined as "best fit" were plotted vs. RSS of the displacement RMS values (SQRT(dispRMSX^2 + dispRMSY^2 + dispRMSZ^2))

Isolator Relative Displacement - X (Tangential) Input



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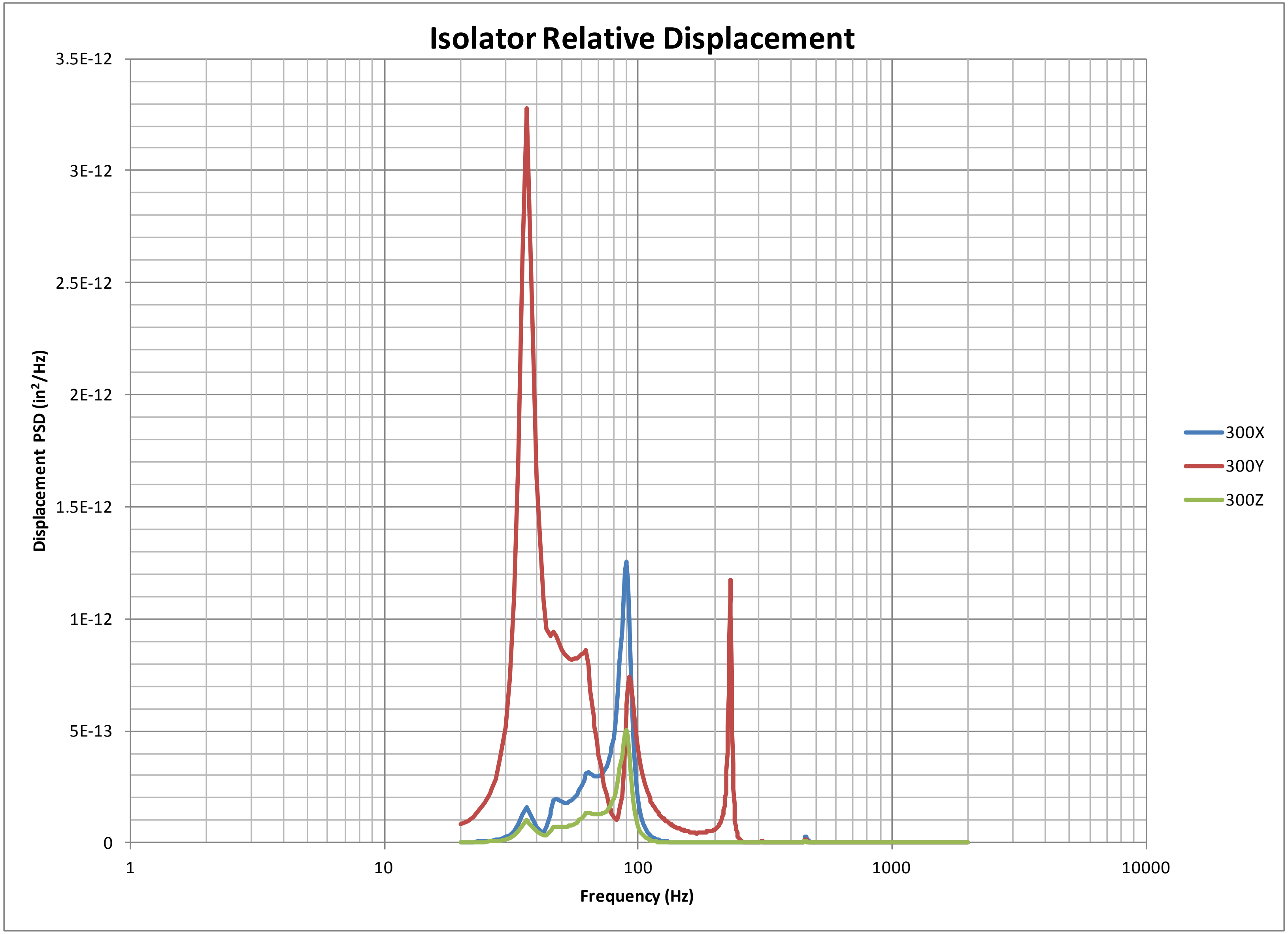
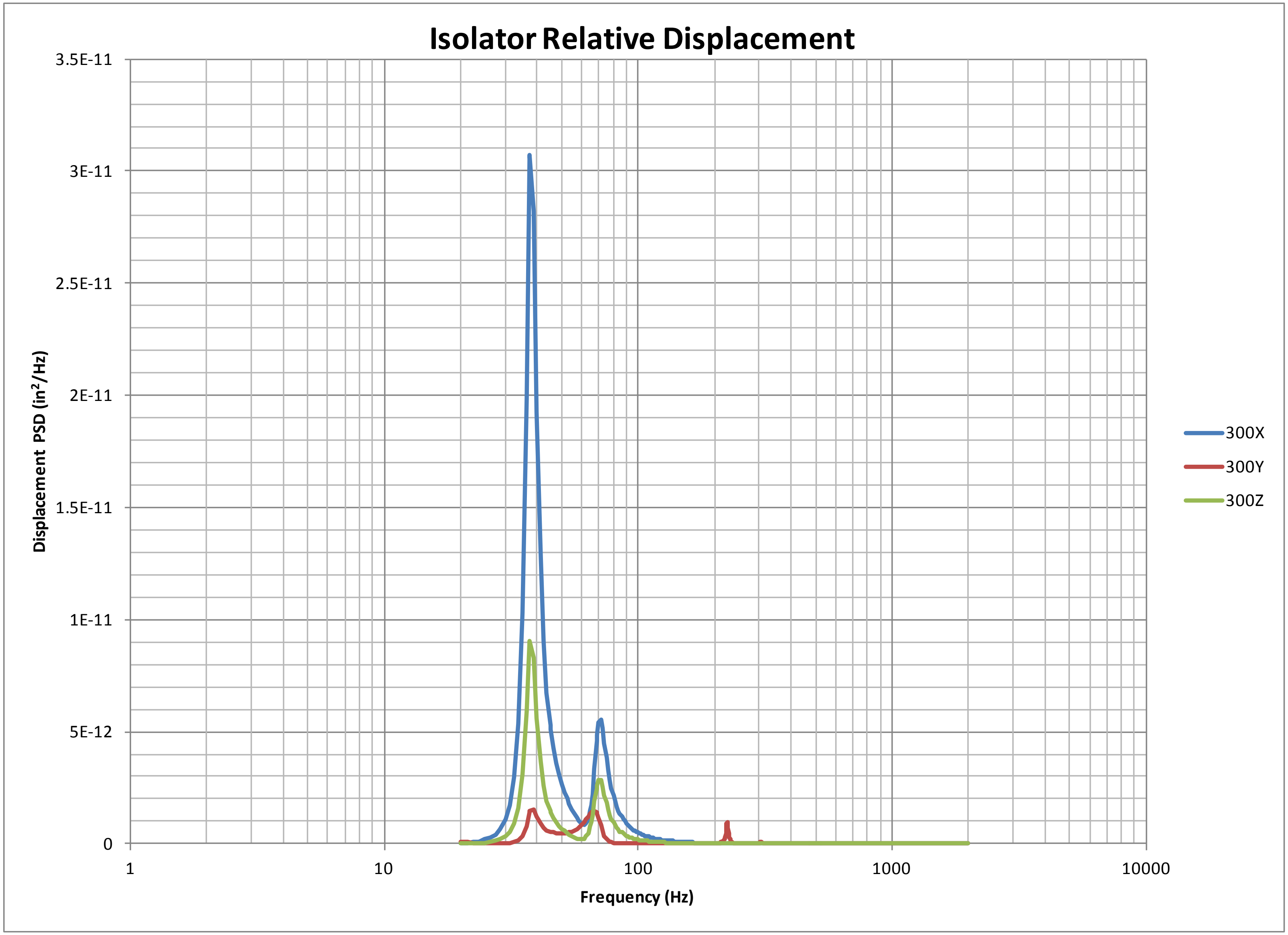
Isolator Relative Displacement - Y (Radial) Input



Isolator Relative Displacement - Z (Axial) Input



AEROSPACE

Small Pallet Set 1 – X (Tangential) 3.65 Grms Results

XORTHO Matrix for Run83 X 3pt65g						
			Analysis Modes			
	Mode #		**2**	**5**	**7**	Frequency
		Freq (Hz)	30.17	84.67	176.07	Diff %
Test Modes	**1**	30.15	0.99			0.1%
	2	84.65		0.99		0.0%
	3	194.88		0.12	0.96	-9.7%

				Design Limits		Set 1 - X 3.65Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	5.84	1518
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.08	281
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	5.06	5566
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	5.84	1518
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.08	281
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	5.03	5533
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.07	1.07E+07

AEROSPACE

Small Pallet Set 2 – X (Tangential) 7.35 Grms Results

XORTHO Matrix for Run83 X 7pt35g						
			Analysis Modes			
	Mode #		**2**	**5**	**7**	Frequency
		Freq (Hz)	29.22	82.40	173.84	Diff %
Test Modes	**1**	28.92	0.99			1.0%
	2	84.00		0.99		-1.9%
	3	186.89		0.13	0.96	-7.0%

				Design Limits		Set 2 - X 7.35Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	4.95	1287
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.08	281
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	4.83	5313
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	4.95	1287
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.08	281
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	4.89	5379
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.07	1.07E+07

Small Pallet Set 3 – X (Tangential) 14.7 Grms Results

XORTHO Matrix for Run83 X 14pt7g						
			Analysis Modes			
	Mode #		**2**	**5**	**7**	Frequency
		Freq (Hz)	24.48	75.50	167.51	Diff %
Test Modes	**1**	23.71	1.00			3.3%
	2	75.00		0.99		0.7%
	3	185.97			0.96	-9.9%

				Design Limits		Set 3 - X 14.7Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	2.45	637
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.04	270
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	4.61	5071
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	2.49	647
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	4.57	5027
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.05	1.05E+07

Small Pallet Set 1 – Y (Radial) 3.65 Grms Results

XORTHO Matrix for Run91 Y 3pt65g						
			Analysis Modes			
	Mode #		**2**	**6**	**10**	Frequency
		Freq (Hz)	36.30	90.29	231.32	Diff %
Test Modes	**1**	35.58	1.00			2.0%
	2	94.26		0.95	0.13	-4.2%
	3	236.25			0.98	-2.1%

				Design Limits		Set 1 - Y 3.65Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	3.22	837
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	3.80	988
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	4.10	4510
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	3.22	837
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	3.84	998
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	4.14	4554
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.04	1.04E+07

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Small Pallet Set 2 – Y (Radial) 7.35 Grms Results

XORTHO Matrix for Run91 Y 7pt35g						
			Analysis Modes			
	Mode #		**2**	**6**	**10**	Frequency
		Freq (Hz)	31.21	88.17	228.95	Diff %
Test Modes	**1**	30.00	1.00			4.0%
	2	93.13	0.15	0.93	0.12	-5.3%
	3	236.41			0.98	-3.2%

				Design Limits		Set 2 - Y 7.35Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	3.25	845
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	2.55	663
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	4.20	4620
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	3.25	845
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	2.55	663
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	4.20	4620
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.04	1.04E+07

Small Pallet Set 1 – Z (Axial) 5.2 Grms Results

XORTHO Matrix for Run125 Z 5pt2g					
			Analysis Modes		
	Mode #		**3**	**10**	Frequency
		Freq (Hz)	37.53	224.55	Diff %
Test Modes	**1**	38.13	0.99		-1.5%
	2	236.25		0.98	-5.0%

				Design Limits		Set 1 - Z 5.2Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	2.08	541
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	2.04	2244
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	2.08	541
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.00	260
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	2.04	2244
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.03	1.03E+07

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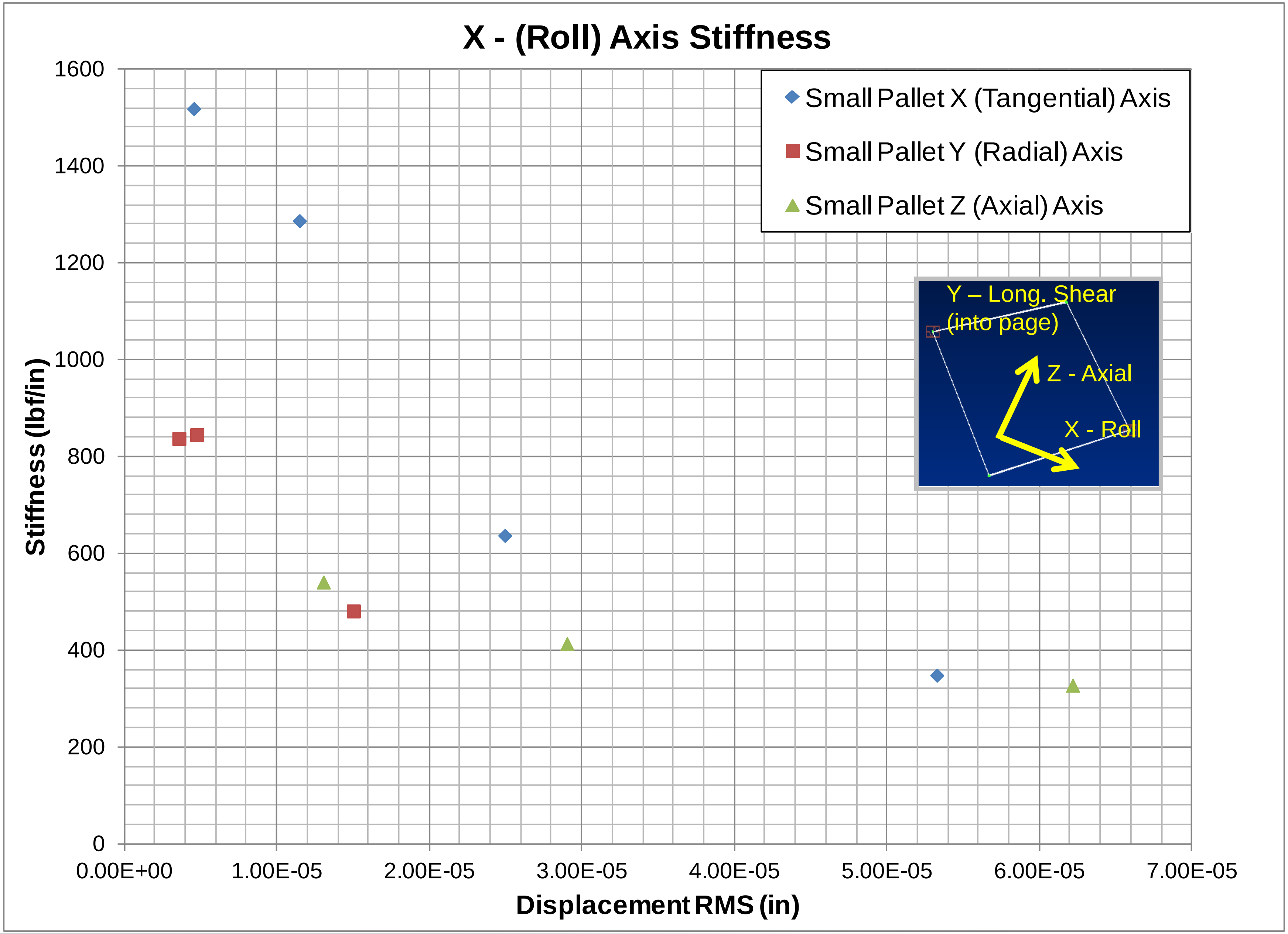
Small Pallet Set 2 – Z (Axial) 10.4 Grms Results

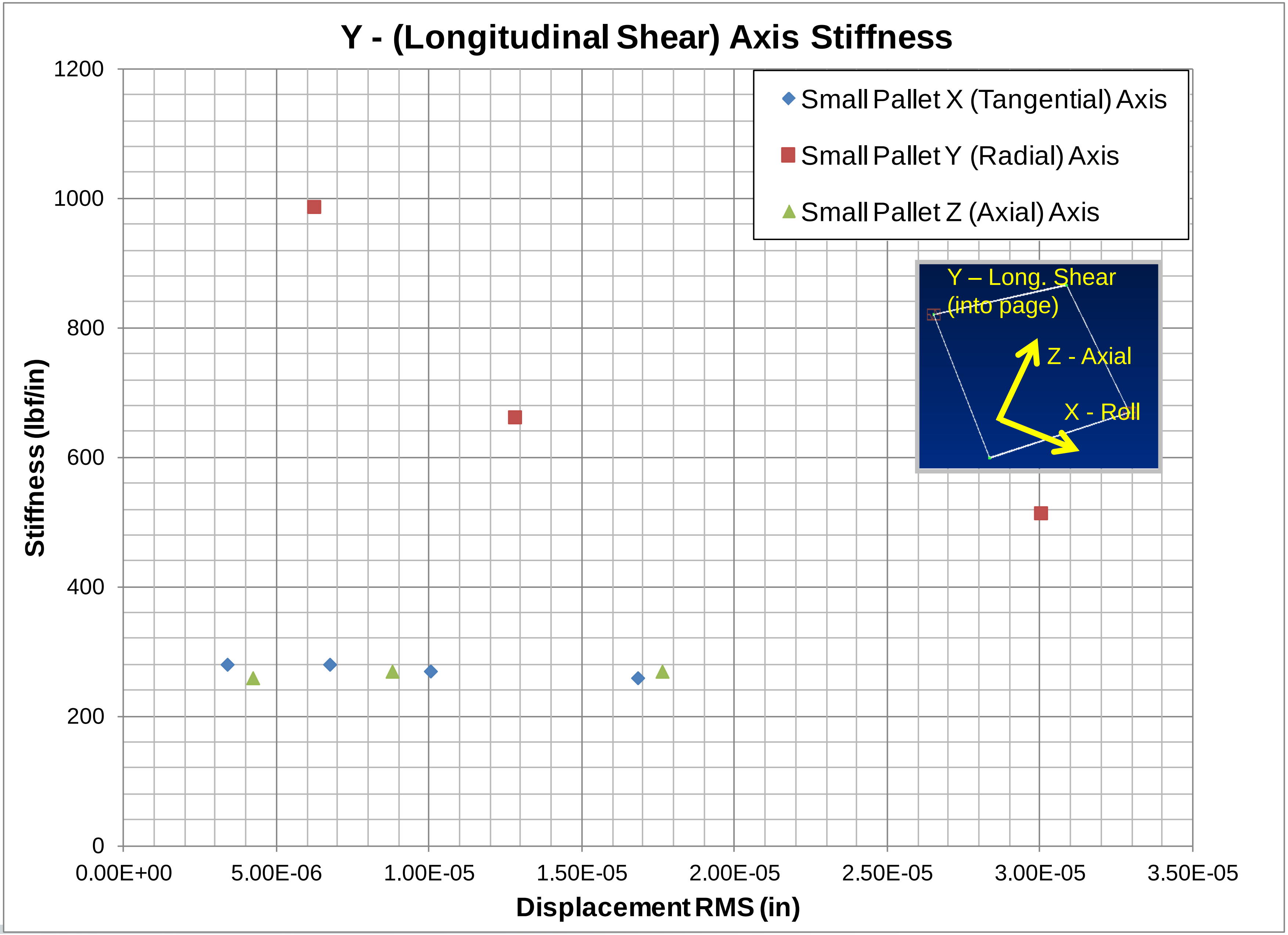
XORTHO Matrix for Run125 Z 10pt4g					
			Analysis Modes		
	Mode #		**3**	**10**	Frequency
		Freq (Hz)	34.11	224.06	Diff %
Test Modes	**1**	34.38	0.99		-0.8%
	2	233.71		0.98	-4.1%

				Design Limits		Set 2 - Z 10.4Grms	
	Design Variables	Description	Initial Value	Lower Bound	Upper Bound	Attune Factor	Value
1	PB164	Isolator CBUSH, K1	260	0.1	10.0	1.59	413
2	PB165	Isolator CBUSH, K2	260	0.1	10.0	1.04	270
3	PB166	Isolator CBUSH, K3	1100	0.1	10.0	1.55	1705
4	PB184	Isolator CBUSH, K1	260	0.1	10.0	1.59	413
5	PB185	Isolator CBUSH, K2	260	0.1	10.0	1.04	270
6	PB186	Isolator CBUSH, K3	1100	0.1	10.0	1.55	1705
7	MA243	Isolator trays, E	9.90E+06	0.90	1.10	1.10	1.09E+07
8	MA253	Isolator Retainer Bars, E	1.00E+07	0.90	1.10	1.02	1.02E+07

Stiffness vs. Displacement RMS (X – Roll Axis) Results



Stiffness vs. Displacement RMS (Y – Long. Shear Axis) Results



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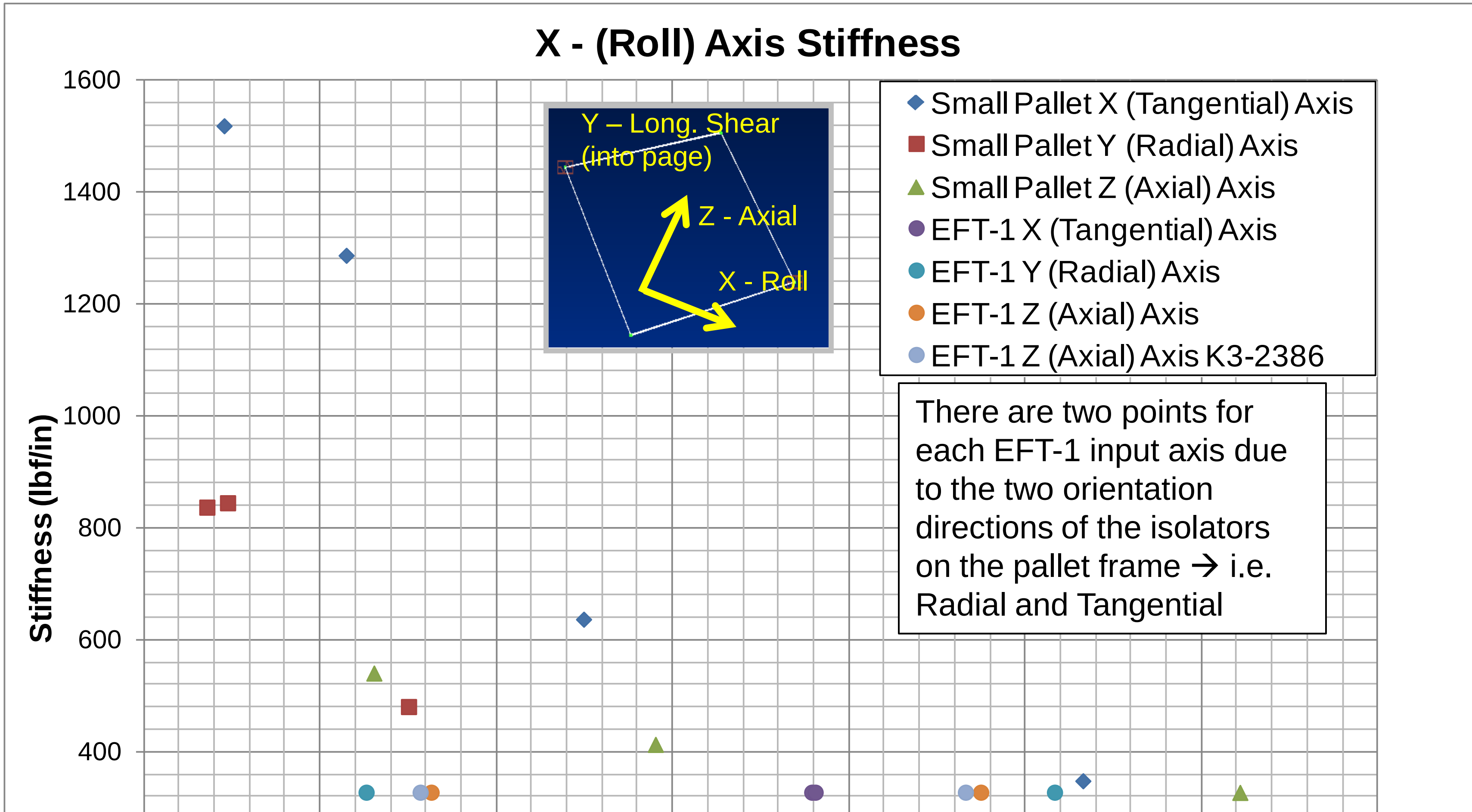
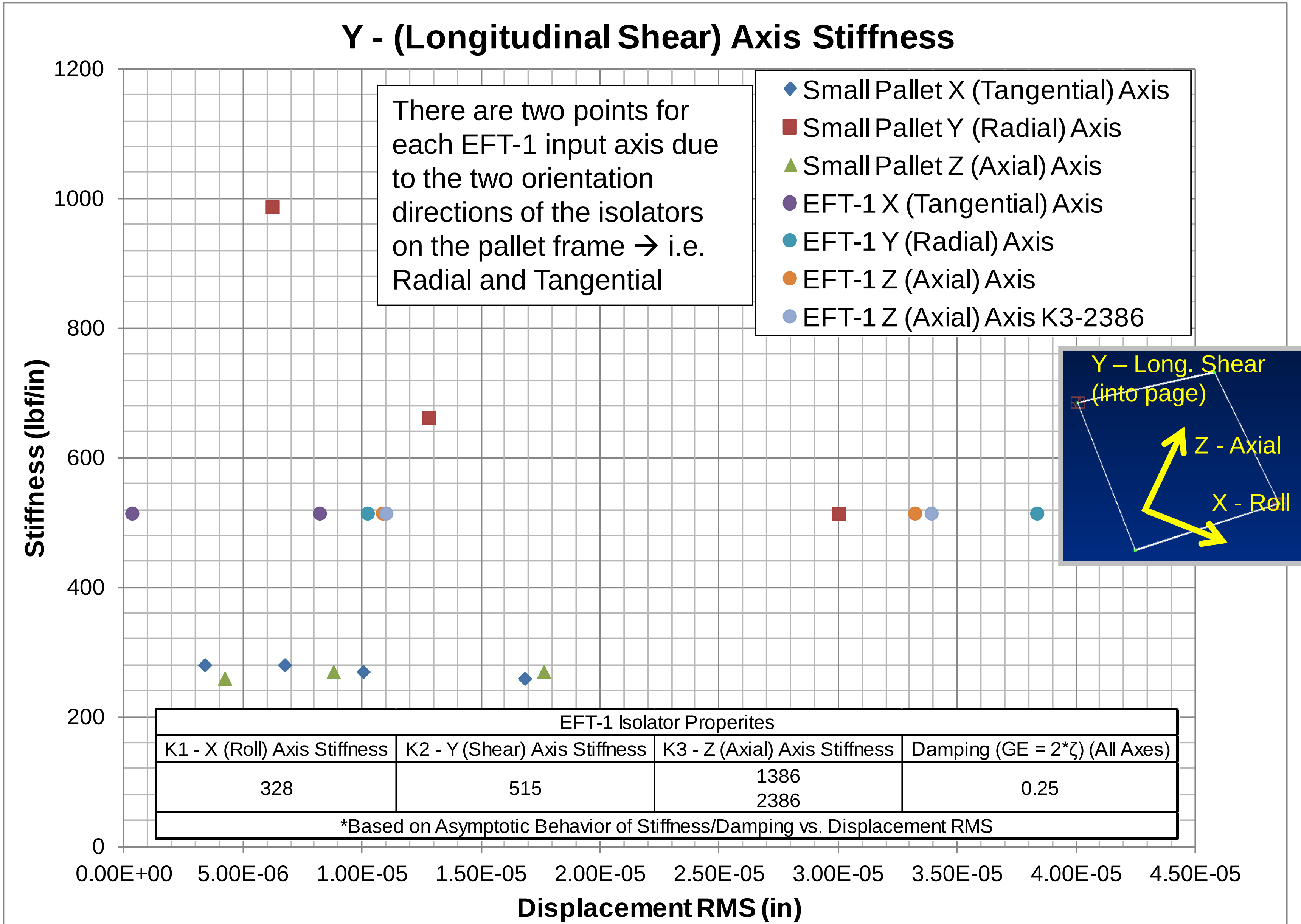
Stiffness vs. Displacement RMS (X – Roll Axis) Results



EFT-1 Isolator Properites			
K1 - X (Roll) Axis Stiffness	K2 - Y (Shear) Axis Stiffness	K3 - Z (Axial) Axis Stiffness	Damping (GE = 2*ζ) (All Axes)
328	515	1386 2386	0.25
*Based on Asymptotic Behavior of Stiffness/Damping vs. Displacement RMS			

Stiffness vs. Displacement RMS (Y – Long. Shear Axis) Results



EFT-1 Isolator Properites			
K1 - X (Roll) Axis Stiffness	K2 - Y (Shear) Axis Stiffness	K3 - Z (Axial) Axis Stiffness	Damping (GE = 2*ζ) (All Axes)
328	515	1386 2386	0.25
*Based on Asymptotic Behavior of Stiffness/Damping vs. Displacement RMS			